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PERFORMANCE OF WIRELESS NETWORKS IN HIGHLY REFLECTIVE ROOMS WITH VARIABLE ABSORPTION

by

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Wireless communications provide opportunities to extend the reach of command and control assets to military members separated from traditional wired networks. Indoor wireless systems are already used in a variety of applications, including office, residential, and even military environments.

However, highly radio frequency (RF)-reflective rooms, such as internal shipboard compartments, well decks, and amphibious combat vehicles, represent extreme conditions for the use of these systems. While wireless communications under such extreme conditions are very difficult or even impossible due to reflected waves, changes in the environment, such as objects or human bodies moving in and out of the room, produce signal power absorption randomly.

The purpose of this thesis is to find an optimized solution for the use of wireless local-area-network devices to provide acceptable throughput in the presence of reflected RF-energy and variable power absorption within reflective compartments. This thesis analyzes the performance of the standard IEEE 802.11ac in reflective environments by testing new available commercial wireless devices in order to provide online access to information and applications from such rooms.

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PERFORMANCE OF WIRELESS NETWORKS IN HIGHLY REFLECTIVE ROOMS WITH VARIABLE ABSORPTION

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LIST OF ACRONYMS AND ABBREVIATIONS

AP	access point
BPSK	binary phase shift keying
COTS	commercial off-the-shelf
CSMA/CA	carrier sense multiple access with collision avoidance
DFT	discrete Fourier transform
DS	direct sequence
EMI	electromagnetic interference
FDM	frequency division multiplexing
FEC	forward error correction
FFT	fast Fourier transform
FH	frequency hopping
GO	geometrical optics
GTD	geometrical theory of diffraction
HT	high throughput
ICMP	Internet control message protocol
IEEE	Institute of Electrical and Electronics Engineers
IFFT	inverse FFT
IP	Internet Protocol
IR	infrared
ISM	industrial, scientific and medical
ISO	International Organization for Standardization
ITU	International Telecommunications Union
LAN	local area network
LHA	landing helicopter assault
LOS	line-of-sight
MAC	media access control
MIMO	multiple-input, multiple-output
MU-MIMO	multi-user multiple-input, multiple-output
OFDM	orthogonal frequency division multiplexing
OSI	open systems interconnection

PEC	perfect electric conductor
PING	packet Internet groper
PO	physical optics
PTD	physical theory of diffraction
QAM	quadrature amplitude modulation
QPSK	quadrature phase-shift keying
RF	radio frequency
SBR	shooting and bouncing rays
SM	spatial multiplexing
USB	universal serial bus
VHT	very high throughput
VoIP	voice over Internet Protocol
WLAN	wireless local area network
WMAN	wireless metropolitan area network
WPAN	wireless personal area network
WWAN	wireless wide-area networks

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I. INTRODUCTION

During the past three decades, the world has seen significant changes in the telecommunications industry. There has been rapid growth in wireless communications, as seen by the large expansion in mobile systems. Wireless communications have moved from systems primarily focused on voice communications to systems dealing with Internet connectivity and multimedia applications [1].

With the Internet and corporate intranets becoming essential parts of daily activities, the world has become increasingly mobile. The traditional wired networks that have been successfully used up to now seem to be inadequate in their ability to meet the challenges of the modern world. Wireless Local Area Networks (WLANs) are a relatively new form of local networks that allow users to be connected and communicate without the need of physical connections. Wireless networks offer several important advantages over fixed (or wired) networks [1], such as:

- Mobility: The ability to freely move within a wireless coverage area with connectivity to existing networks.
- Ease and speed of deployment: WLANs do not require cables through walls or ceilings, and they can be installed in places that are very difficult to implemented wired local area networks.
- Flexibility: Wireless networking allows users to quickly form small-group, ad hoc networks for support of an impromptu meeting; simplifies moving between the offices of a building; since the wireless network medium is available everywhere, the expansion of wireless networks is easy and quick.
- Cost: In some cases, using wireless networks can reduce costs. Although the initial investment could be expensive, in the future a wireless network will have a negligible monthly operating cost, as well as low barriers to adding new users.

Despite the aforementioned advantages, WLANs have some limitations compared to wired networks, as follows [2]:

- Throughput: Wireless networks are slower than wired networks. Although a great increase in the wireless data rate has occurred during the last decade, the difference is considerable. The available bandwidth is an upper limit on the speed of wireless networks.

- Interference and Reliability: Radio waves can suffer from a number of propagation problems, mainly due to multipath propagation and electromagnetic interference (EMI), causing denial of service.
- Data and Access Security: the wireless medium cannot be controlled and it is easy to be accessed by anonymous attackers. To address this problem, proper protection is needed to ensure data privacy and user authentication; encryption algorithms are used, reducing the throughput of the wireless system.

WLANs provide opportunities to extend the reach of command and control assets to military members separated from traditional wired networks. However, highly radio frequency (RF)-reflective rooms, such as internal shipboard compartments, well decks, amphibious combat vehicles, or armored vehicles represent extreme conditions for the use of these communication systems.

A. SCOPE OF THESIS

The purpose of this research is to identify and explore a solution for the use of WLAN devices to provide acceptable throughput in the presence of reflected RF-energy and variable signal absorption by analyzing the propagation behavior of radio waves using technology features to mitigate the effects.

The analytical study of wireless communications performance under these particular conditions provides a better understanding of the phenomena in order to produce recommendations applicable to any organization that will operate within reflective areas. This research was done using commercial off-the-shelf communications devices as their expected employment is unlikely to require the robustness associated with similar military grade systems. Further, the choice of IEEE 802.11 as the WLAN implementation is due to the large base of common consumer devices available that are suitable for adoption by military applications.

B. THESIS OUTLINE

This thesis is organized as follows. Chapter II gives an overview of the IEEE802.11 Standard, specially oriented to the amendment IEEE802.11ac, its propagation characteristics, and problems associated with the implementation of a WLAN within reflective rooms. Chapter III presents a propagation simulation under

reflective conditions pertinent to a simplified version of a well deck. Chapter IV covers the implementation of an indoor 802.11ac WLAN, within a reflective environment, materialized by a shipping container, providing results of the conducted performance measurements. Finally, Chapter V summarizes the results of this thesis and suggests topics for future research.

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II. BACKGROUND

Wireless local area network technology has a long history that dates back to the 1970s, with roots as far back as the 19th century, when numerous inventors and scientists such as Michael Faraday, James Clerk Maxwell, Heinrich Rudolf Hertz, Nikola Tesla, Thomas Edison, and Guglielmo Marconi created many theories about electromagnetism and experimented with radio frequency. Wireless communications technology is one of the most important applications of this theory [3].

Wireless technology has been used since the beginning of the 20th century. In the early stages, wireless communications technology was dominated by military usage and supported according to military needs and requirements. During the last half of the century, with increasing civilian mobile services, commercial wireless communication systems have been taking the lead.

A. WIRELESS COMMUNICATIONS

Over the past three decades, the world has become mobile and less tethered to wired infrastructure due to the evolution of this technology. As a result, the traditional wired networks that have been successfully used seem to be inadequate in their ability to meet the challenges of the increasingly mobile modern world.

The use of electromagnetic waves for wireless communications is very attractive because direct physical connections, such as wires or cables, are not required. There have been some remarkable aspects to the fast growth in wireless communications, as seen by a large expansion in mobile systems. Wireless communications have proved to be effective solutions to provide data due to their advantages over the wired services. Some of these advantages are simplicity, ease of use, and compatibility with existing networks, without the need for expensive and time-consuming rewiring. Other advantages include providing services for a larger number of users, roaming, and elimination of wiring around and inside buildings. In addition, wireless communications have more immunity to natural and manmade disasters.

Different wireless technologies have been developed and implemented for applications, such as cellular systems and Wi-Fi technology. The Institute of Electrical and Electronics Engineers (IEEE) is a professional society that creates and maintains standards used for communications, such as the 802.3 Ethernet standards for wired networking. From an Internet protocol stack perspective, the IEEE 802 family of standards addresses the physical and data link layers. Wireless systems consist of wireless wide-area networks (WWAN), such as cellular systems; wireless metropolitan area networks (WMAN), such as 802.16 WiMAX; wireless local area networks (WLAN), such as the 802.11 WiFi; and wireless personal area networks (WPAN), such as 802.15 Bluetooth and ZigBee [4].

The handsets used in many of these systems, especially 802.11-based devices, have complex functionalities. These small, low-power-consuming devices are mass-produced at low costs, which have accelerated their widespread use. New advancements in online applications have increased network traffic considerably, resulting in an extraordinary growth in demand for bandwidth. One of the consequences of this phenomenon is the fast growth of the mobile Internet, which emerged as the Internet has become an everyday tool and users have changed their expectations of what data access means [1].

The IEEE 802.11 technology, commonly referred to as Wi-Fi (a moniker used to market 802.11 WLAN technologies), is a standard oriented to providing local area network (LAN) communications using radio frequencies, also known as a WLAN [3]. In the indoor environment, WLANs provide more flexibility than that achieved by the wired LAN. WLANs are implemented as an extension or alternative for wired LANs to transmit and receive data over the air, combining data connectivity with user mobility.

The range of a WLAN depends on its usage and the environment in which the system is operated. It may vary from 30 meters inside a building to several thousand meters in an outdoor environment, if directional antennas are used. The communication is established in a part of the radio spectrum designated as license-free in many countries, allocated in the bands between 2.4 to 2.5 GHz and 5.15 to 5.875 GHz.

IEEE 802.11 has had several amendments since the standard was first published in June 1997. In particular, 802.11ac, one of the most recent amendments, is already available in the market, and ready to implement optimal solutions, providing enhancements by using more sophisticated modulation schemes, cryptographic algorithms, and new technologies such as multiple-input-multiple-output (MIMO) data streams, in order to take full advantage of wireless solutions.

B. WIRELESS LOCAL AREA NETWORKS

WLANs are data communications systems implemented as an extension or as an alternative to wired LANs by using radio frequency (RF) technologies, providing high flexibility and minimizing the need for wired connections. They provide high-speed, reliable data communications in indoor and outdoor areas, combining connectivity with user mobility [1]. From the military point of view, mobility, also considered as a combat multiplier, is of special interest due to the ability to allow a remote user to stay connected to the network while moving or otherwise not physically attached to the network. Mobility allows real-time information access, regardless of user location, for faster and more efficient decision making.

In general, a hand-held terminal with an RF interface card connects to an access point (AP) that supports multiple users simultaneously. The AP is connected to a wired network and works as a gateway between wired and wireless users, routing data between the two networks. Further, the WLAN can be used independently of wired networks to link multiple nodes or devices without a connection to wired networks; such a network is often referred to as ad hoc.

WLAN users are capable of roaming from one AP to another, providing coverage for a larger area by using multiple APs. Commercial off-the-shelf WLANs generally use a part of the radio spectrum designated as license-free. The band, 2.4 to 2.5 GHz, has been designated by the International Telecommunications Union (ITU) as such, and is available in that way in most countries of the world.

The range of a WLAN depends on the conditions of the channel, considering variables such as usage and environment where the wave has to propagate. It can vary

from 30 meters inside a solid building to several hundreds of meters in an outdoor environment. Interference, caused by simultaneous transmission of electromagnetic waves in the same frequency by multiple users and by multipath fading, affects the performance in terms of range and achieved throughput.

1. IEEE 802.11 Standards

The International Organization for Standardization (ISO) is responsible for the creation of the Open Systems Interconnection (OSI) model, which has been a conceptual model that characterizes and standardizes the functions of a communication system by partitioning them into layers [3]. In general, the Internet Society, through the Internet Engineering Task Force, establishes standards for layers above the physical and data link layers, deferring standards for those two layers to organizations specific to electrical and electronics systems. One such organization is the Society of International Electrical and Electronics Engineers (IEEE). The IEEE defines a set of standards specific to local area networks. Of these, the 802.11 standards define technologies pertinent to the physical layer and the media access control (MAC) sublayer of the data-link layer of the OSI model for wireless LANs [1]. Collectively, these are referred to as WiFi.

The original 1997 release of the standard defined an infrared (IR) and an Industrial Scientific and Medical (ISM) band, using two different spread spectrum modulation techniques: frequency hopping (FH) or direct sequence (DS). Also, carrier sense multiple access with collision avoidance (CSMA/CA) was used as the MAC method. All devices compete for access on a random basis, which can be difficult for distant devices that could be repeatedly interrupted by devices within range of the intended receiver but beyond the range of the attempting transmitter [5]. This effect is known as the *hidden node* problem, which is illustrated in Figure 1.

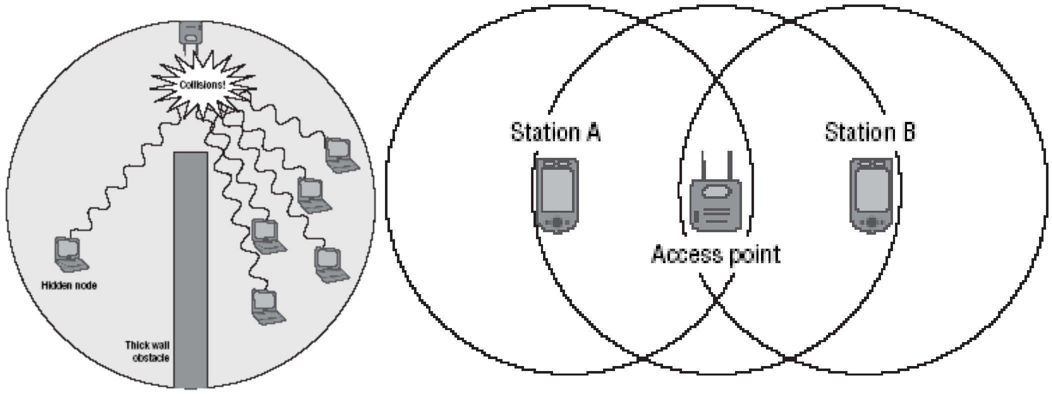

Figure 1. Hidden node: obstruction and large coverage cell.

Figure 1 shows two typical cases of hidden nodes: obstructions, where an obstacle makes it impossible for a group of users to listen the other group; and large coverage, where station A and station B cannot hear each other. In both cases, collisions may occur at the access point. Real-time services, such as Voice over Internet Protocol (VoIP), can be very difficult to implement given that they require a predetermined quality of service which may be hampered by such access collisions [5].

The standards specify operations in the unlicensed 2.4- and 5-GHz bands. Currently, there is a draft standard under development that specifies operations in the 60-GHz band, named the 802.11ad Standard. The addition to the capabilities of the physical layer interfaces defined “a,” “b,” and “g,” 802.11n incorporated Multiple-Input, Multiple-Output (MIMO) technology, and “ac” improved this feature [5]. The most important amendments to the standard are listed in Table 1.

Table 1. IEEE 802.11 technology evolution, from [6].

Standard	Release date	Band (GHz)	Bandwidth (MHz)	Max Data Rate	Advanced Antenna Technologies
802.11	1997	2.4	20	2 Mbps	N/A
802.11b	1999	2.4	20	11 Mbps	N/A
802.11a	1999	5	20	54 Mbps	N/A
802.11g	2003	2.4	20	54 Mbps	N/A
802.11n	2009	2.4, 5	20, 40	600 Mbps	MIMO, up to four spatial streams
802.11ac	2013	5	40, 80, 160	6.93 Gbps	MIMO, MU-MIMO, up to eight spatial streams

The 802.11b amendment uses the original CSMA/CA media access method, with a data rate up to 11 Mbps at 2.4 GHz. It employs DSSS, with complementary code keying (CCK) as the modulation technique, usually configured as point-to-multipoint, but with high-gain antennas, it can be used in outdoor point-to-point applications [5].

The 802.11a uses the same MAC protocol but defines a 5 GHz-band physical layer based on a 52-subcarrier Orthogonal Frequency Division Multiplexing (OFDM) technique (48 data carriers and four pilots in a 20-MHz bandwidth). The subcarriers can be modulated with different schemes according to channel conditions. These modulation scheme options include binary phase shift keying (BPSK), quadrature phase-shift keying (QPSK), 16-quadrature amplitude modulation (16-QAM), or 64-quadrature amplitude modulation (64-QAM); providing data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps [7].

The 802.11g physical layer implemented the OFDM format, providing up to 54 Mbps to the 2.4GHz band and backwards compatibility with 802.11b.

The 802.11n introduced several major MAC sublayer and physical layer advances, such as MIMO and channel bonding. By implementing MIMO, the system can provide greater data rate without an increase in spectrum bandwidth using spatial multiplexing (SM). This increases the data rate from 150 Mbps without SM to 300 and 450 Mbps with SM given that the transmitter and receiver have at least two antennas.

Channel bonding utilizes two adjacent channels simultaneously, doubling the channel bandwidth from 20 to 40 MHz, carrying twice as much data compared to previous standards. The counterpoint is that it substantially increases the risk of interference by other nearby networks due to the increased bandwidth.

2. The 802.11ac Standard

The most recently implemented IEEE WiFi standard is 802.11ac, which utilizes dual band wireless technology, supporting connections on both the 2.4 GHz and 5 GHz Wi-Fi bands simultaneously. It offers backward compatibility to 802.11b/g/n and data rates up to 1300 Mbps on the 5 GHz band, and up to 450 Mbps on 2.4 GHz band. There are several improvements introduced by the standard, most of them connected with the physical layer, to achieve better data rates and multiple user performance. Some of these improvements are highlighted as follows [3].

Wider RF channel bandwidth: The 40-MHz channel of 802.11n was extended to 80- and 160-MHz channels.

More spatial streams: While 802.11n defines up to four spatial streams, 802.11ac allows up to eight, doubling the number defined by the previous standard.

Multi-user MIMO (MU-MIMO): This new feature allows an access point to transmit different streams to several clients simultaneously using beam forming, or spatial filtering, a signal processing technique used for directional signal transmission or reception by combining elements in a phased array in such a way that signals at particular angles experience constructive interference, while others experience destructive interference. MU-MIMO increases the utilization of the network by transmitting to multiple users simultaneously.

Modulation and coding: 256-QAM, rates 3/4 and 5/6, were added as optional modes, extending the previous highest rate of 802.11n from 65 Mbps to 78 Mbps, and 86.7 Mbps, respectively.

Table 2 shows the main characteristics of the standard, to be used according to the quality of the received signal.

Table 2. 802.11ac theoretical link rates, from [6].

Channel Bandwidth	**Transmit–Receive Antennas**	**Modulation and Coding**	**Throughput**
40 MHz	1x1	256-QAM 5/6	200 Mbps
40 MHz	3x3	256-QAM 5/6	600 Mbps
80 MHz	1x1	256-QAM 5/6	433 Mbps
80 MHz	2x2	256-QAM 5/6	867 Mbps
80 MHz	3x3	256-QAM 5/6	1.3 Gbps

These improvements introduced by the new standard are very useful to mitigate the negative effects of wave reflections in reflective areas. Wave propagation and how it interacts with the environment are the most important factors to be considered when using these technologies in order to take full advantage of wireless solutions.

C. THE PHYSICS OF PROPAGATION

Propagation is the process whereby a signal is carried between a transmitter and a receiver. One of the most important advantages of signal transmission based on electromagnetic waves is that no material link, such as wire or cable, is required between the transmitter and the receiver. Propagation considerations have an important influence on the systems design. The signal frequency and the environment determine which propagation mechanisms are dominant. These mechanisms, in general, involve different physical processes and mathematical models to represent them [5].

Radio propagation in urban areas often consists of reflected and diffracted waves produced by multipath propagation. The simplest case to treat is the propagation in open areas free from obstacles but, in general, propagation over the earth and the water invokes at least one reflected wave.

For closed areas, such as indoors, tunnels, and underground passages, there is not a model developed because the environment has a complicated structure. However, some models can be applied for specific cases.

One of them is the Rayleigh model, used for urban area propagation and when the environmental structure is random. The Rician model can be used when the propagation path is line-of-sight, such as in tunnels and underground passages [1].

As an electromagnetic wave, radio wave propagation is impacted by three main behaviors: *absorption, reflection, and refraction* [8].

1. Absorption, Reflection, and Refraction

Absorption is caused by some materials that convert the electromagnetic energy into heat. It is one of the most important causes of attenuation, given that most materials will absorb some amount of energy depending on their characteristics. Bricks and concrete walls will absorb significantly, as well as water, which can absorb energy [1]. Such attenuation due to heat generation is also present in wired networks limiting their single-link length.

Reflection occurs when the wave propagating in one medium hits another medium with different electromagnetic properties. In this case, part of the energy is absorbed or refracted through the second medium, and the other part is reflected back to the first medium. Considering Wi-Fi frequencies, in an outdoor environment, waves can reflect off buildings, roads, bodies of water, and even the earth surface. In an indoor environment, waves reflect off surfaces such as doors and walls. Metallic objects, in general, cause the most important reflections but other materials such as glass and concrete may also produce them. The law of reflection establishes that a reflected ray lies in the plane of incidence and has an angle of reflection equal to the angle of incidence (both relative to the normal) [1].

The incident wave will also be partially refracted, unless the second medium is a perfect electric or magnetic conductor. In this particular case, there will be no refraction and the incident wave is completely reflected back into the first medium [8]. A sample ray diagram of a plane wave incident on an interface between two mediums is illustrated in Figure 2.

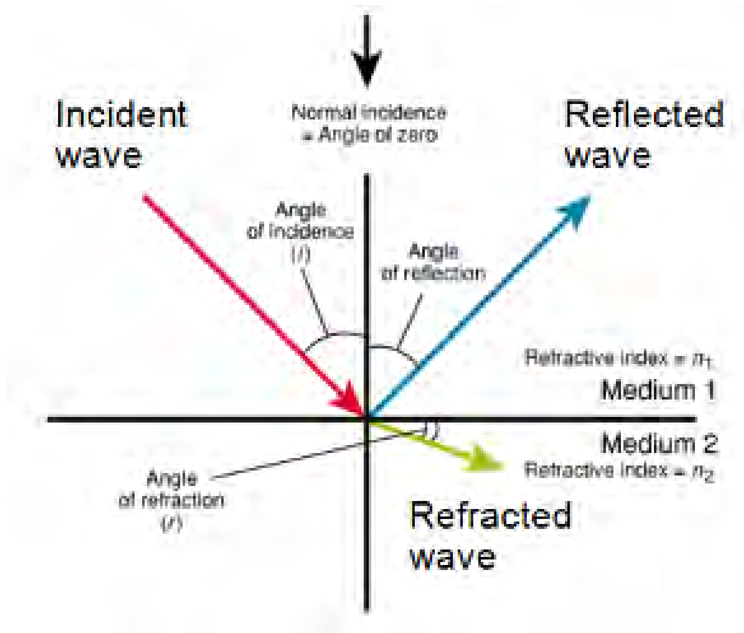

Figure 2. Reflection and refraction.

Refraction is the bending of the propagation direction as the signal passes through material with different electromagnetic properties, unless it is a perfect conductor. In an outdoor environment, atmospheric conditions cause refraction due to different temperatures, densities, and pressure. In an indoor environment, certain materials may also refract the signal [1].

Furthermore, the refraction law establishes that a refracted ray lies in the plane of incidence and has an angle of refraction *r* that is related to the angle of incidence *i* by:

$$n_2 \sin(r) = n_1 \sin(i)$$

This equation is known as Snell's law. Each of the symbols n_1 and n_2 is a dimensionless constant, called the index of refraction, and it is a characteristic of the medium involved in the refraction.

2. Diffraction

Diffraction is the bending of a propagating radio wave around an object, typically caused by a partial blockage of the line of propagation, such as a small hill, a building, or a sharp edge, producing wavelets into a shadowy region [1].

The secondary wavelets diffracted by the edge, propagate behind the obstacle into the shadow. The intensity of diffraction depends on the geometry of the obstacle, and amplitude and polarization of the incident electromagnetic wave. Figure 3 illustrates edge diffraction around a building. It also serves as an important factor to spread waves in an indoor environment, especially in reflective areas, producing fading, or reduced signal strength as discussed below, due to changes in the wave phase.

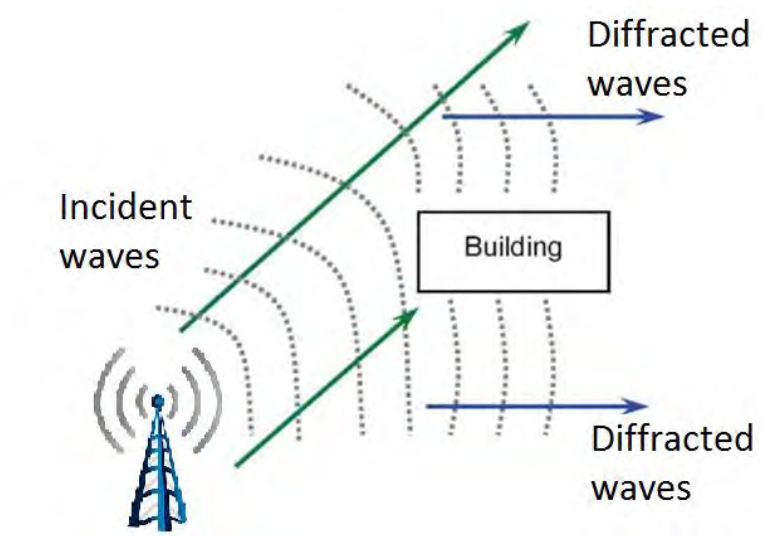

Figure 3. Edge diffraction on a building.

3. Scattering

Scattering occurs when the wave impinges on a rough surface or an object small relative to the wavelength. It can be described as multiple reflections, causing the signal energy to spread out in all directions. Small objects scatter more or less uniformly in all directions as shown in Figure 4. Traffic lights, street signs, and foliage are typical scattering objects [1].

In indoor environments, relative to the wavelength at 2.4 GHz (0.125 m), typical scattering objects range from small desk tools to items the size of furniture and humans.

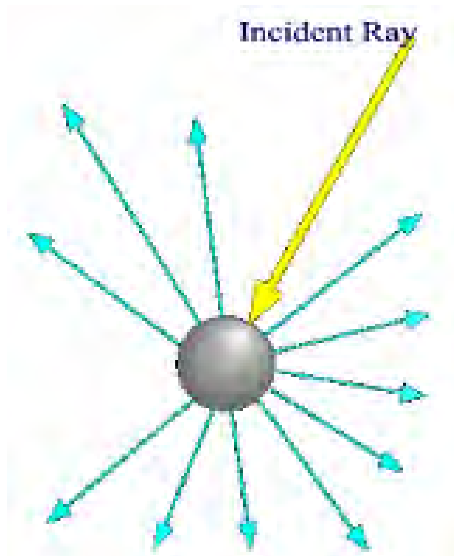

Figure 4. Scattering on a small object.

4. Radio Wave Propagation

Radio waves are part of the electromagnetic spectrum. They propagate through space as travelling electromagnetic waves, combining electric and magnetic fields, both always exist together because a change in the electric field generates a magnetic field and vice versa.

They arrive at the receiver from different directions and paths, to add as vectors at the receiving antenna, producing a resultant signal with large or small amplitude, depending upon the phase relation among them, and causing amplitude and phase fluctuations, called *fading* [1], as illustrated in Figure 5.

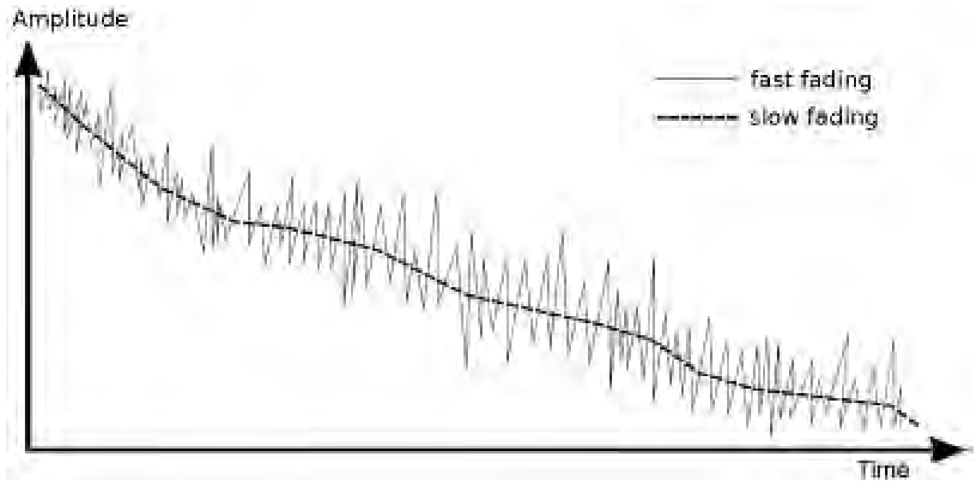

Figure 5. Signal fading.

The received signal power decreases as the distance between the transmitter and the receiver increases. In free space, this signal attenuation is proportional to the second power of the distance, however, in urban and indoor areas, this proportionality can change to the fourth or fifth power due to reflections on obstacles. Also, received signals can be higher than the direct path component when electromagnetic waves add to one another, and much lower when they cancel each other out. Such adding or canceling of signal power depends on the relative phase shifts of the original signal due to differences in time of arrivals for the various multiple paths.

The signal power fluctuates around a mean value, across the distance from the transmitter, and these fluctuations can have a short or long period. Short period means that the signal power fluctuates more rapidly, caused by small movements of the transmitter, receiver, and surrounding objects, and producing a local multipath in the area close to the transmitting antenna, usually over distances of about half a wavelength. This effect can be observed in Figure 5 and is referred to as *short-term* or *fast fading*.

Farther from the transmitter, fluctuations have a long period, caused by movement over distances large enough to produce variations in the overall path, referred to as *long-term* or *slow fading* (Figure 5) [5].

Fast fading results when the signal travels from the transmitter to the receiver following different paths. The phases of the signal vary in time and the multipath

components interfere with each other at the receiver antenna causing great variability. For locations shadowed by buildings, a *Rayleigh distribution* is the most common probability density function used to model this phenomenon. In the case of indoor environments, where sometimes the base station is visible to the mobile station, wherein the direct path presents a dominant contribution, the *Rician distribution* is the typical distribution function used for modeling [9].

5. Free Space Attenuation

The simplest wave propagation case is that of direct wave in free space. In this case, there are no obstructions due to the earth's surface or other obstacles, resulting in the line-of-sight (LOS) propagation between the transmitter and the receiver as the only path bearing consideration.

The received power, P_r, at the receiving station located at a LOS distance, d, from the transmitter is given by the Friis transmission equation [1]:

$$P_r = P_t \left(\frac{\lambda}{4\pi d} \right)^2 G_{Tx} G_{Rx}$$

where:

$P_r =$ received power

$P_t =$ transmitted power

$\lambda = \frac{c}{f} =$ wave length

$c =$ velocity of electromagnetic waves in the free space (3 x 10^8 m/s)

$f =$ carrier frequency in Hz

$d =$ distance between transmitter and receiver

$G_{Tx} =$ gain of the transmitting antenna

$G_{Rx} =$ gain of the receiving antenna

The equation can be rewritten, considering only the free space loss L_{FS}, as:

$$\frac{P_t}{P_r} = L_{FS} = \left(\frac{4\pi d}{\lambda}\right)^2$$

Expressing it in decibels (dB) yields:

$$L_{FS} = 20\log\left(\frac{4\pi d}{\lambda}\right)(dB)$$

From this equation, the free-space attenuation increases 6 dB (four times) if the distance d between transmitter and receiver is doubled. When doubling the frequency, such as going from the 2.4 GHz band to the 5 GHz band, the attenuation also increases by 6 dB.

Figure 6 shows how the power is attenuated through the first 150 meters for 2.4 GHz and 5.8 GHz. Each 10 dB loss represents a reduction by a factor of 10 in the received signal power.

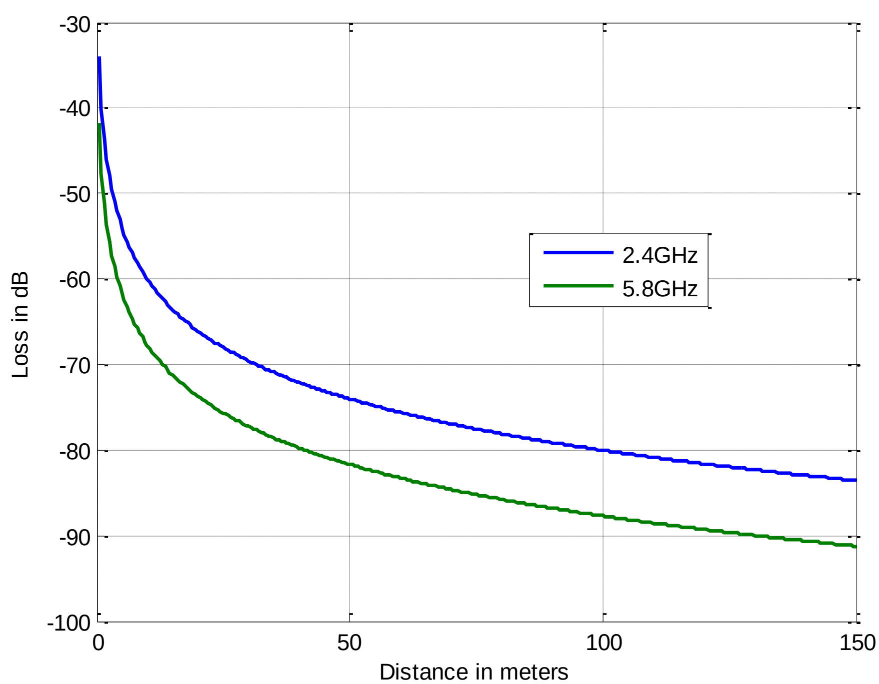

Figure 6. Free space attenuation–Loss vs. distance (generated by Matlab).

6. Multipath Channels

A radio frequency signal can take different paths to reach its destination due to its reflection, diffraction, and scattering on its path from the transmitting to the receiving antenna. Multiple copies of the same signal are received resulting in variations in amplitude, phase, and time, producing an effect called multipath.

Amplitude variations can produce weak signals, sometimes impossible to be detected; phase differences produce constructive and destructive signal interference, and deviation in arrival time results in symbols overlapping each other in time, known as inter-symbol interference [2]. Additionally, relative motion between transmitter and receiver, or the objects between them, can be observed in the frequency domain as a Doppler shift, proportional to the relative velocity of the objects [2].

Figure 7 shows the complexity of the multipath phenomenon in an indoor environment between a given source and receiver pair using simulation. The number of rays emanating from the transmitter and arriving at the receiver, with different amplitudes and phases, can be observed.

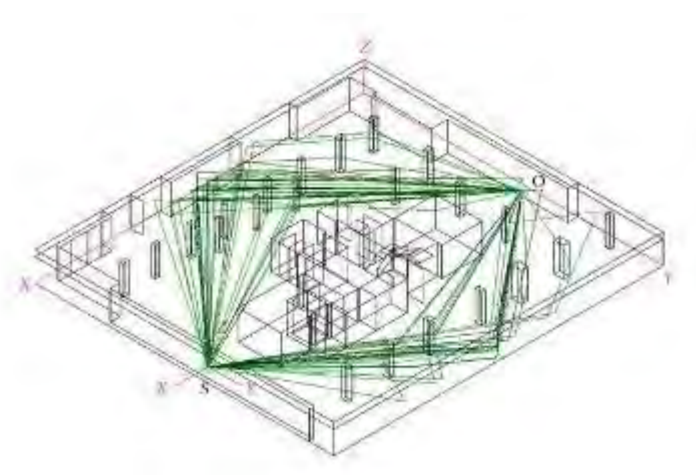

Figure 7. Multipath phenomenon in an indoor environment.

As mentioned before, IEEE 802.11ac includes new solutions to mitigate multipath propagation effects, particularly *orthogonal frequency division multiplexing* (OFDM), and *multiple-input, multiple-output* (MIMO) technique. In a typical indoor environment,

multiple RF signals sent by a MIMO radio will take multiple paths to reach the MIMO receiver, in general, using dipole antennas.

D. ANTENNA FUNDAMENTALS

An antenna can be defined as a region of transition from a guided wave to a free space wave. It is the interface between the radio system and the external environment. There are antennas of different sizes and shapes for different uses, such as radio wave communication systems, radio, and television broadcasting transmission and reception, and radar systems [2].

Antennas are not isotropic radiators, meaning that they do not radiate the same power in all directions. The shape of the pattern describes the directionality of the antenna [1]. The half-wave dipole antenna is the simplest one to build and it is often used to describe the gain of other antennas. As shown in Figure 8, it consists of two identical conductive elements with a total length of half the wavelength λ of the frequency to be used. In real systems, other types of antennas are used to provide higher gain than a dipole antenna [1].

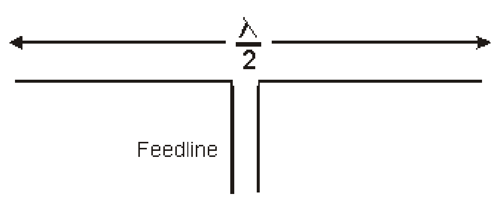

Figure 8. Half-wave dipole antenna.

Most Wi-Fi wireless LAN access points are shipped from the factory with the common half-wave dipole, 5-inch long, straight, black antenna as standard equipment. Many 802.11 access points use several of these antennas to implement space diversity. This type of antenna is referred to as *omnidirectional* because it radiates in all directions around the plane perpendicular to the antenna shaft.

1. Antenna Radiation Pattern

The radiation pattern is an angular representation of the distribution of the radiated power from, or received by, the antenna, as a function of direction angles, usually using polar coordinates [5]. Figure 9 shows a radiation pattern for a dipole, including a three-dimensional model generated by software Savant 4.0 [10].

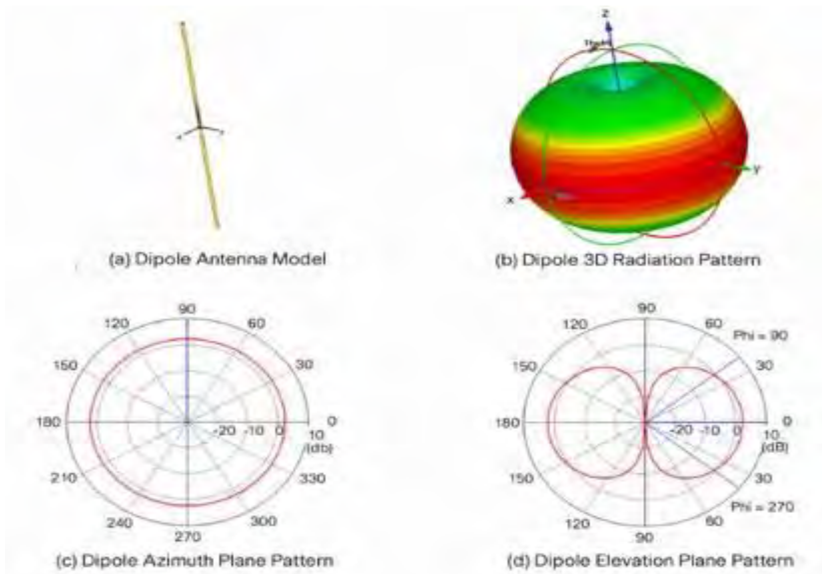

Figure 9. Antenna radiation pattern.

An antenna pattern has main, side, and back lobes, as seen in Figure 10. The angular width of the main lobe, or beamwidth, is the angle between first nulls and is generally represented by half-power beam, also known as the 3-dB beamwidth, as a 3-dB drop represents a decrease in the power by a factor of two [5].

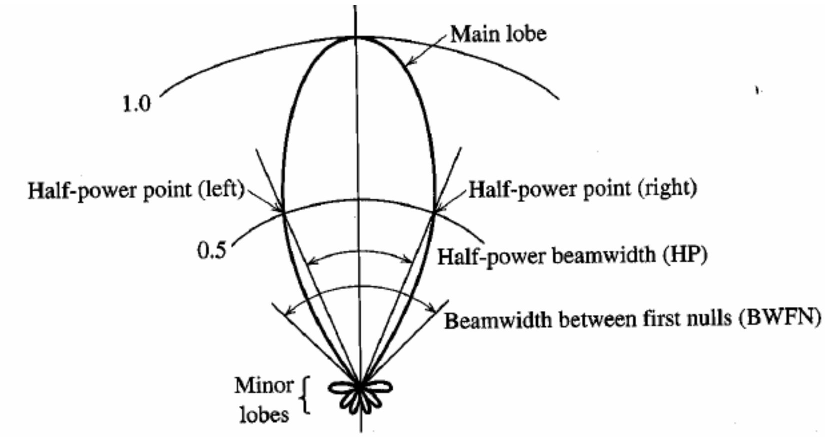

Figure 10. Sample of a polar plot of antenna radiation pattern, from [5].

2. Antenna Directivity

The directivity is the ratio of maximum power density in the main beam direction of the radiation pattern to the average power density of the antenna. An ideal antenna radiates the energy fed into it equally in every direction in space. This theoretical model is called an isotropic radiator and its directivity is equal to one. Real antennas radiate more strongly in some directions than in others, and in general, are quoted relative to the isotropic radiation [5].

3. Antenna Gain

Every antenna has the directivity reduced due to losses. This effect is known as the efficiency, η. Antenna gain is usually stated as the peak gain mathematically; it is the product of directivity and efficiency. In general, gain is expressed in decibels relative to the isotropic radiator, typically measured in dBi (Decibels relative to an isotropic radiator) or in dBd (Decibels relative to a lossless resonant half-wave dipole radiator) [5].

4. Antenna Polarization

The antenna polarization refers to the orientation of the electric field vector of the wave radiated by the transmitting antenna as it travels along the direction of propagation.

According to how vectors behave along its path, the wave polarization can be elliptical, circular, or linear, as shown in Figure 11, by using the simulation software EMANIM [11].

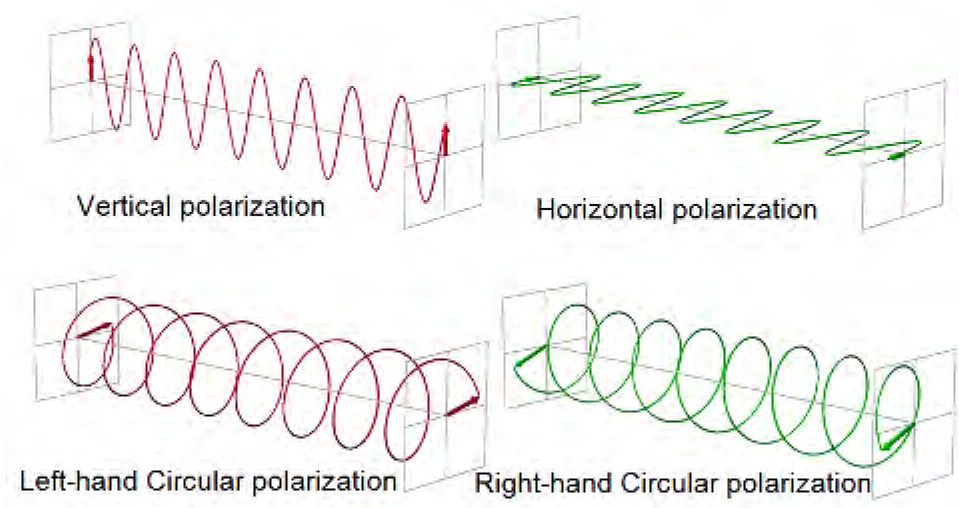

Figure 11. Wave polarization.

In most wireless applications, the transmitting and the receiving antennas are linearly polarized, either vertically or horizontally. Polarization mismatch loss occurs if the transmitting and receiving antennas are not similarly polarized. A linearly polarized antenna used to receive a circularly polarized wave will recover only one-half the power relative to circularly polarized antenna of the same directivity. Similarly, a circularly polarized antenna will receive only half the power from a linearly polarized wave compared with a linearly polarized antenna having the same directivity. For linearly polarized antennas, the received power will be at maximum when both the received signal and the antenna have the same polarization, and theoretically zero when they are rotated in 90 degrees. This consideration is important to be taken into account for mobile communications [5].

E. ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

As mentioned before, OFDM is one of the techniques that can help to mitigate multipath effects. It is a multicarrier modulation scheme, consisting of dividing the

information to be transmitted into a large number of bit streams at lower bit rates individually and modulating each on an individual orthogonal carrier [5]. OFDM can be seen as either a modulation technique or a multiplexing technique. If the multiple carriers are used for a single user the technique is modulation, whereas if the separate streams are allocated to different users, then it is multiplexing. OFDM increases the robustness against frequency selective fading and narrowband interference because in a single carrier system fading or interference can cause the entire link to fail, while, in a multicarrier system, only a small percentage of the carriers will be affected. These errors can be corrected using a forward error correction (FEC) protocol [7].

A classic parallel data system can be obtained if the total frequency band is divided into N non-overlapping subchannels, and each subchannel is modulated with a different symbol. Many carriers are spaced apart in such a way that they can be received using conventional filters and demodulators, using guard bands between adjacent carriers in the frequency domain. This concept results in an inefficient use of the available spectrum. The solution is that multiple carriers, each with a signaling data rate *b*, are spaced *n times b* Hz (n = 1, 2, 3, …) apart in frequency from the other carriers, optimizing the bandwidth occupation for the same data rate R. The overlapping multicarrier technique is accomplished by reducing crosstalk between carriers, which means that the different modulated carriers have to be orthogonal among them. The word orthogonal means that there is an exact mathematical relationship among the frequencies of the carriers, arranging the carriers in an OFDM signal, such that the carriers are linearly independent, which is the case if the carrier spacing is a multiple of b [7].

Figure 12 shows the contrast between an orthogonal multicarrier technique versus a conventional multicarrier technique. In this case, almost 50 percent of the bandwidth W can be saved; thus, more information can be transmitted in the same bandwidth by using OFDM [7].

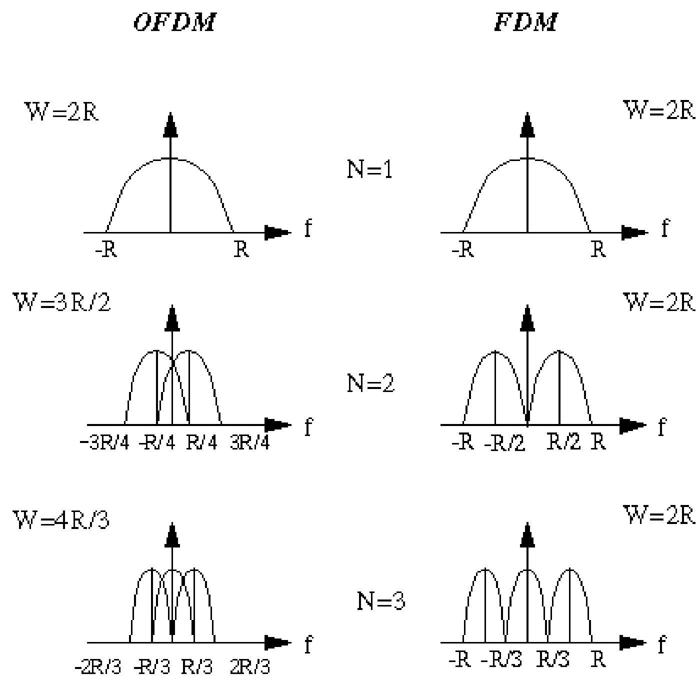

Figure 12. Concept of OFDM signal, from [4].

Figure 13 shows that at the center frequency of each subcarrier, there is no crosstalk from other channels. Therefore, using a Discrete Fourier Transform (DFT) at the receiver and calculating the correlation values with the center frequency of each carrier, it is possible to recover the transmitted data with no crosstalk. Moreover, a completely digital implementation can eliminate the banks of subcarrier oscillators and coherent demodulators required by frequency division multiplexing (FDM). Such an implementation is accomplished by performing the Fast Fourier Transform (FFT), an efficient implementation of the DFT, at both transmitter and receiver [7].

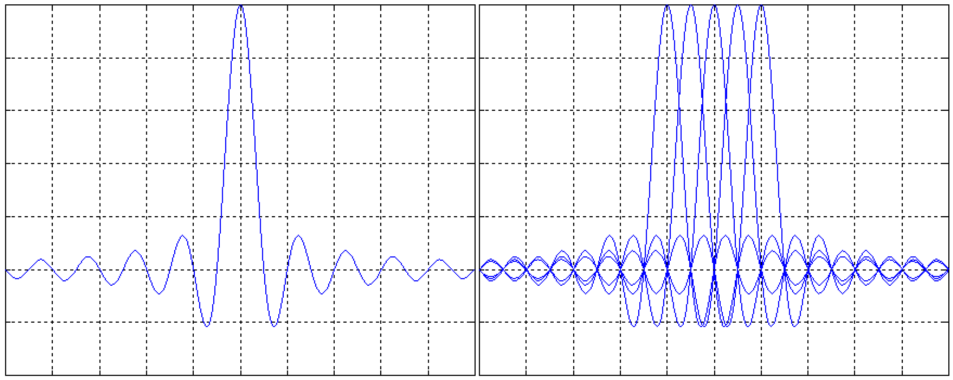

Figure 13. Spectra of OFDM subchannel (left) and OFDM signal (right), from [7].

An OFDM modulation scheme makes efficient use of the spectrum by allowing overlap of adjacent channels, resulting in more resistance to frequency selective fading than single carrier transmissions, and providing better protection against co-channel interference and impulsive parasitic noise [5].

The basic principal of operation is to divide the bit stream to be transmitted into a number of lower data rate subcarriers. The standard defined initially 48 data subcarriers and four pilot subcarriers, for a total of 52 subcarriers. Each lower data rate bit stream modulates a separate subcarrier, using a convolutional code and bit interleaving. The subcarriers are combined using inverse FFT (IFFT) and transmitted. At the receiver, the carrier is converted back to a bit stream by using FFT and combining the lower data date subcarriers [1].

As an example, Figure 14 shows how OFDM was implemented by the different WLAN standards. The increase in channel width delivers slightly more usable bandwidth because the ratios of pilot tones to subcarriers decrease. The diagram shows non-high throughput (non-HT), high throughput (HT), and very high throughput (VHT) versions, for 20 to 40 and 80 MHz bandwidths. The 160-MHz channel is always treated as two 80-MHz channels for subcarrier assignment, whether contiguous or not.

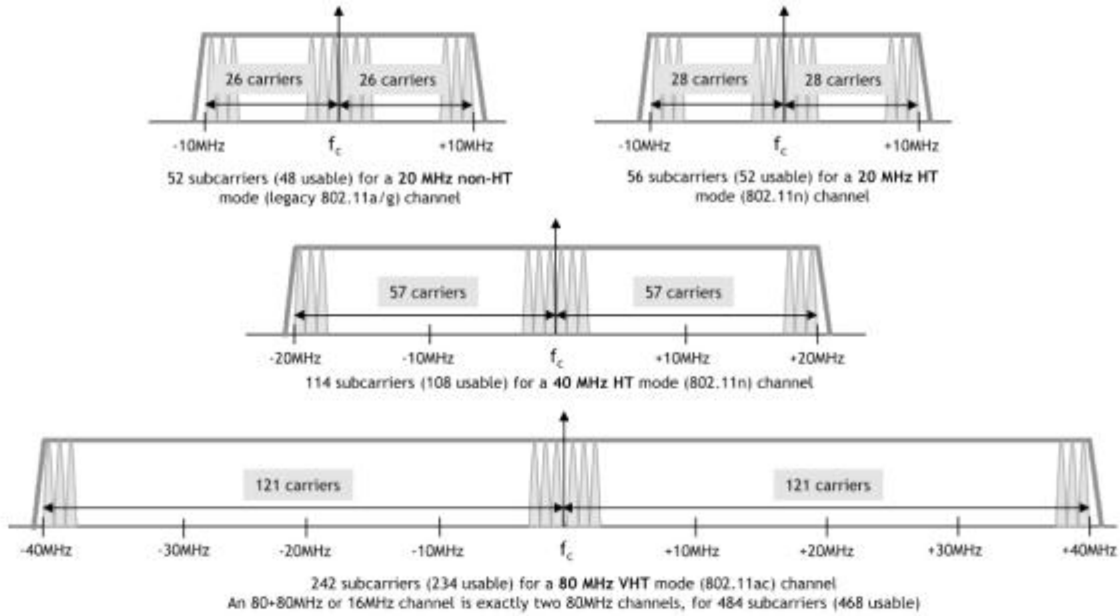

Figure 14. OFDM subcarriers used in 802.11a, 802.11n and 802.11ac.

F. MULTIPLE-INPUT, MULTIPLE-OUTPUT

Increasing the transmit power to improve the reliability of a fading wireless is usually an expensive or impractical solution. One of the solutions is the implementation of diversity schemes in which multiple copies of the same signal are transmitted over different propagation channels. During deep fading periods on one channel the probability of experiencing a simultaneous deep fade on the other channel(s) is very low [8].

All of the channels have to be sufficiently independent to experience different fading behaviors. For example, this can be accomplished by transmitting the same signal at different times, frequencies, or polarizations, or by using multiple transmitting and receiving antennas conveniently separated in the physical space. This last case is known as a multiple-input, multiple-output (MIMO) system [8].

Smart antenna techniques, such as MIMO systems, can provide better ability for a system to achieve increased data throughput. MIMO systems use multiple antennas at both the transmitter and the receiver to increase the capacity of the wireless channel. With MIMO, different signals are transmitted simultaneously in the same bandwidth over

independent channels, provided the multipath environment is rich enough, and then separated at the receiver, as shown in Figure 15. Using four antennas at the transmitter and receiver has the potential to improve the system capacity by four times the data rate of a single antenna system without increasing transmit power or bandwidth [1].

Figure 15. Different MIMO configurations used by 802.11n and ac.

Considering a scheme of *m* independent propagation channels, each channel with a probability of a given fading level, *q*, the probability of fading all channels simultaneously will be q^m. As an example, if m = 4 and q = 0.1 (10%), then q^m=0.0001, or 0.01 percent. It means that the resulting probability of fading level is in this case 1,000 times lower.

G. SUMMARY

This chapter focused on the theory behind wireless propagation and different technologies implemented by WLAN standards. Using appropriate software, a simulation of wireless propagation in a highly reflective room under WLAN conditions is presented in Chapter III.

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III. SOFTWARE SIMULATION

In this chapter, several simulations in an indoor reflective environment and their results are described. The purpose of the simulations is to determine how multipath propagation affects the signal stability.

A. SOFTWARE TOOLS

Savant is a Windows-based program developed by Delcross Technologies. It is one of several commercially available software packages for propagation and scattering simulation for predicting the performance of antennas in their intended installation environment, such as on aircraft, ships, cars, spacecraft, buildings, and other platforms.

Savant can determine the signal level for wireless networks with predefined inputs, such as, building geometry, antenna types, frequency, and polarization. The purpose of this research is to analyze the effects of multipath propagation on wireless LAN systems operating inside a highly reflective room, particularly in a well deck.

In addition, SketchUp Version 14.0 software was chosen to generate the 3-D model. It is a user-friendly CAD software product, supplying a very effective toolset to create, analyze, render, edit, and build a 3D model precisely. SketchUp supports many file formats. For this project, the *.obj format was chosen. A sample of SketchUp is illustrated in Figure 16.

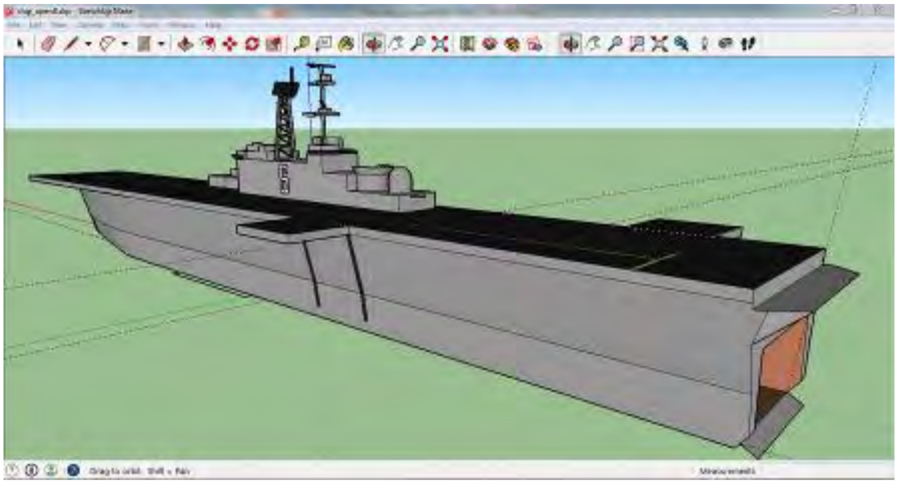

Figure 16. A sample SketchUp editor.

1. Designing the Model

The model for this research built using the SketchUp software is a simplified version of an *amphibious assault ship*, including particularly the well deck. Figure 17 shows the ship model.

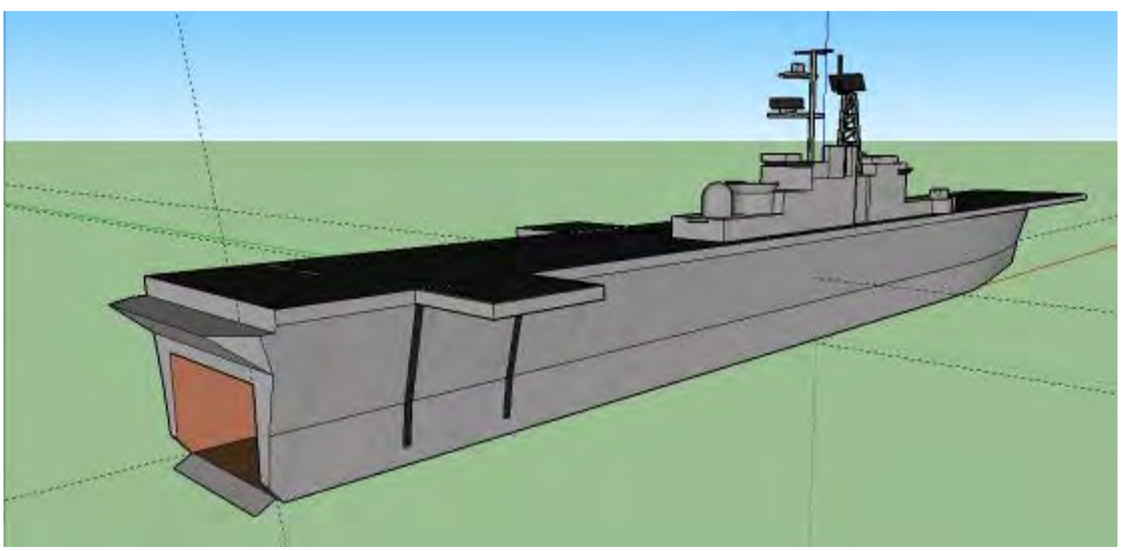

Figure 17. Ship model.

After exporting the model as a *.obj file, it was imported into Savant, and a flat ground plane was located under the ship to simulate the sea. In this way, the model is composed of two different materials, and each one has different electrical characteristics:

the metallic structure of the ship and the sea water. Figure 18 and Figure 19 show this model.

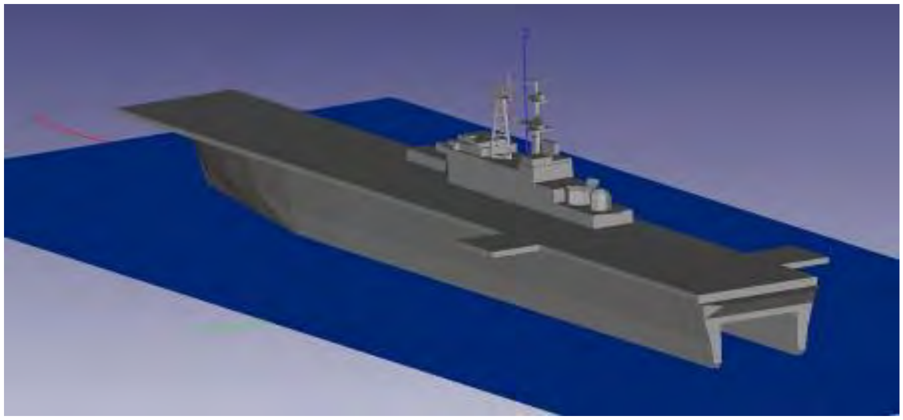

Figure 18. Ship model with the sea, door opened.

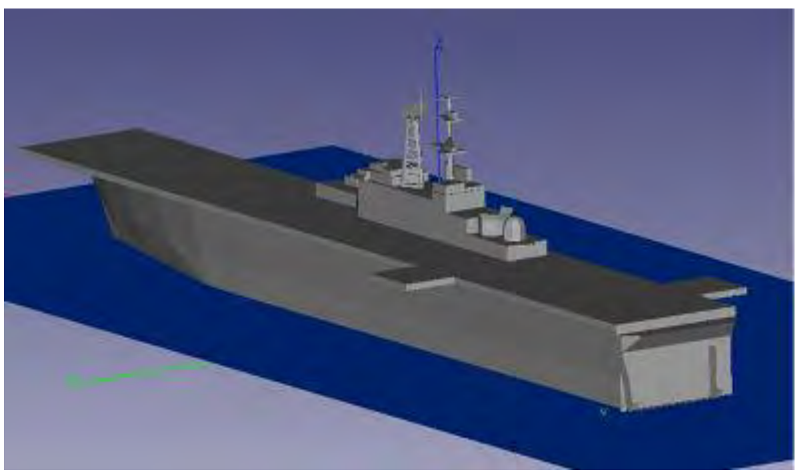

Figure 19. Ship model with the sea, door close.

2. Simulation Methodology

Propagation and scattering analyses generally fall into two categories: ray based techniques (geometrical optics, GO, and the geometrical theory of diffraction, GTD) or current based (physical optics, PO, and the physical theory of diffraction, PTD). For these ray methods, the sum of all reflected, transmitted, and diffracted rays arriving at the observation point is computed. The field strength is determined by the value of the

reflection, transmission, and diffraction coefficients along the ray paths, and their divergence and spreading factors [10].

Shooting and Bouncing Rays (SBR) are considered a *hybrid* method because they contain elements of both ray and current methods. SBR can be thought of as a hybridization of GO and PO [10].

In this case, this simulation is oriented to determine the amount of reflection a wave can have before arriving at the receiving antenna, and how this amount changes for different positions.

3. Savant Overview

Savant uses a 3D ray tracing engine to characterize electromagnetic wave propagation. The ray tracing simulation engine is based on the SBR method, which is an asymptotic method, and therefore relevant to modeling electrically large platforms and environments.

Specifically, Savant uses high-density ray tracing to approximate the surface currents induced by the antenna. These currents are then radiated to determine the influence (blockage, reflection, and diffraction) of the platform on antenna radiation and antenna-to-antenna coupling [10].

B. INDOOR PROPAGATION APPLICATION

This section details the model setup and simulation, including their results, for an indoor propagation simulation.

1. Model Setup

The model is composed of two materials with different propagation characteristics. One of them is the steel, the main structural material of the ship, and the other one is the seawater. The steel was considered as a perfect electric conductor (PEC) for the simulation, a reasonable approximation to its electromagnetic behavior.

All the simulation components (CAD model and antennas) can be observed in Figure 20. In this case, part of the model was cut away to observe the interior and the

placement of the antenna. Figure 20 shows the model with the Y-axis clipped. The antenna and multiple reflections for a one-ray simulation can be seen in this figure.

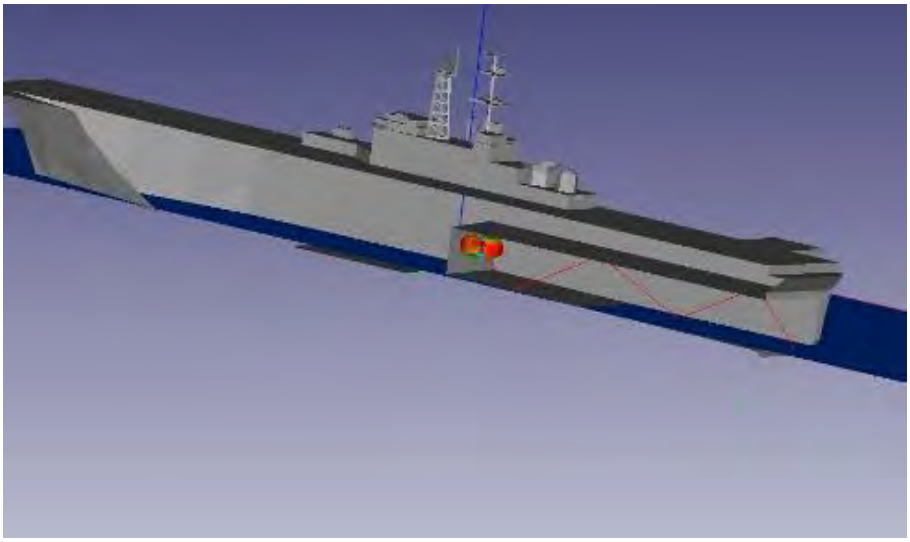

Figure 20. Ship model with Y-axis clipped.

The model was built according to an approximation of a Tarawa-class amphibious assault ship. In this case, the USS Peleliu (LHA-5) well deck dimensions were considered as follows in Table 3.

Table 3. Well deck dimensions.

Dimension	**Meters**	**Feet**
Length	100	328.1
Height	12	39.4
Width	20	65.6

The simulation parameters were set to provide conditions similar to actual ones. Savant has several generic antenna types available. A half-wave dipole was used, considering that commercial WLAN devices in general are provided with this kind of antenna.

2. Simulation

Savant computes the components of the electric field at observation points with three-dimensional coordinates (x, y, z). The observation plane is a set of points where the electromagnetic field is computed. Using the graphical tool, the observation points can be modified in order to observe a certain plane.

The propagation conditions were simulated for both frequencies involved 2.4 and 5.8 GHz to develop an approximation of the real propagation in such an environment. Clipping the z-axis, Figure 21 and Figure 22 show the model, including the antenna model in the reflective area and water within the well deck when the door is open.

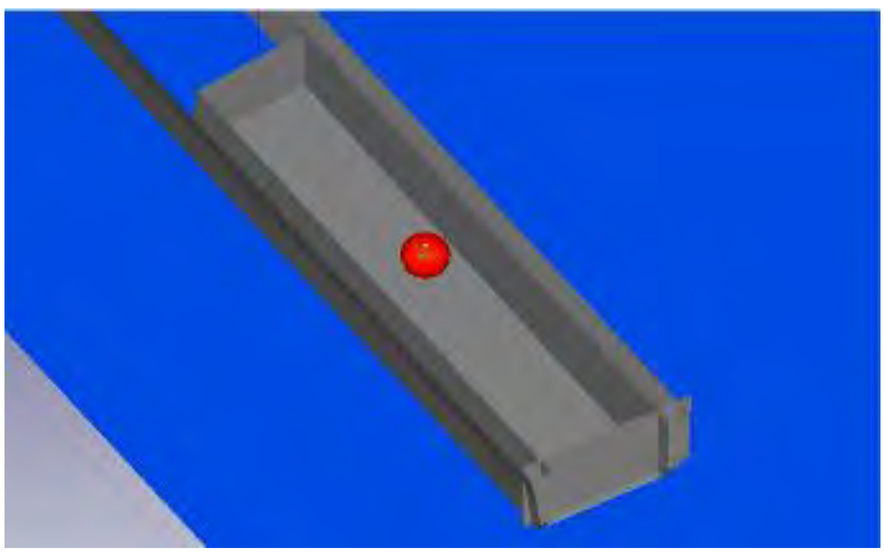

Figure 21. Ship model with Z-axis clipped, closed door.

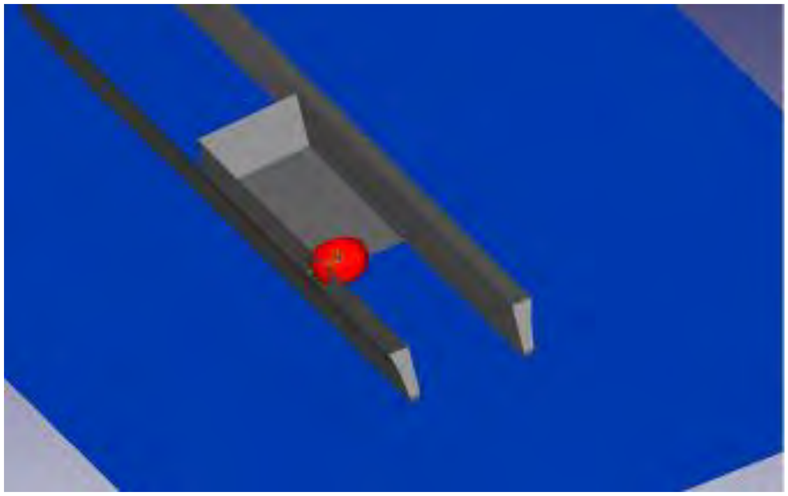

Figure 22. Ship model with Z-axis clipped, open door.

After executing ray tracing, the power distribution could be observed for different positions of the antenna. These power distributions in the well deck are shown in Figures 23, 24, and 25, considering the door open. The colors of the rays indicate the different power levels, according to the scale on the right-hand side of the figures.

The upper deck has been clipped to show the rays in the interior. The ray tracing itself is relatively independent of wavelength; however, material properties can change with frequency. Therefore, the resulting transmission, reflection, and refraction may be frequency dependent. The total power field is the sum of the incident and scattered rays.

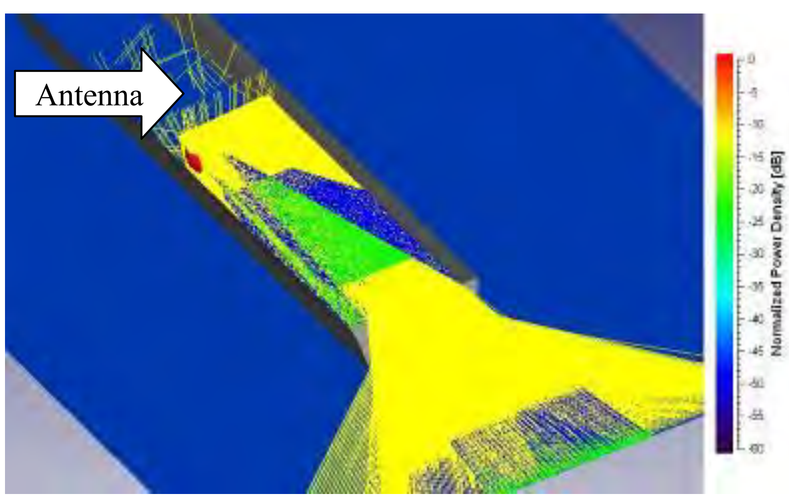

Figure 23. Savant ray trace output—2.4 GHz—antenna in a corner; door open.

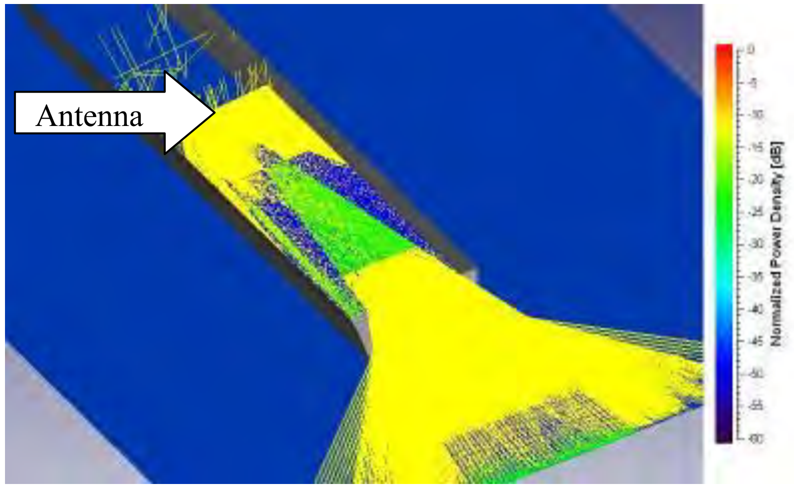

Figure 24. Savant ray trace output—2.4 GHz—antenna in the center; door open.

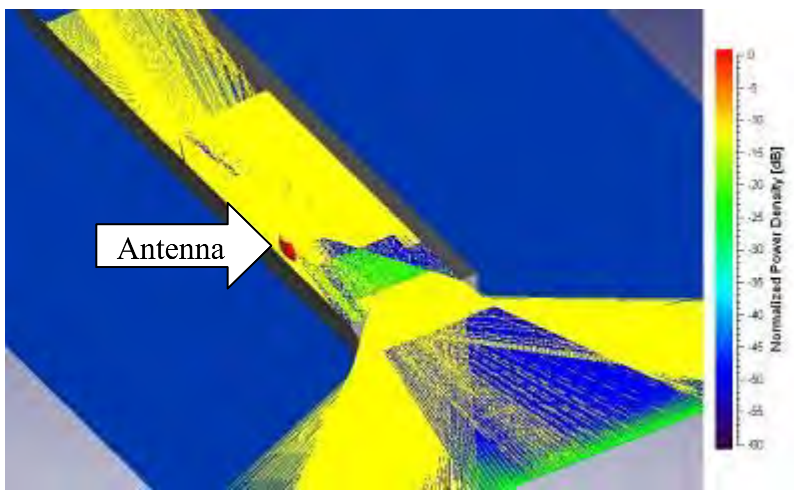

Figure 25. Savant ray trace output—2.4 GHz—antenna in the center; door open.

The different colors indicate the normalized power density in the well deck according to the scale on the right-hand side of the figures. The power distribution in the room changes abruptly in some areas, decreasing to very low levels (blue rays). Considering the door is closed, the simulation results as shown in Figure 26 and Figure 27.

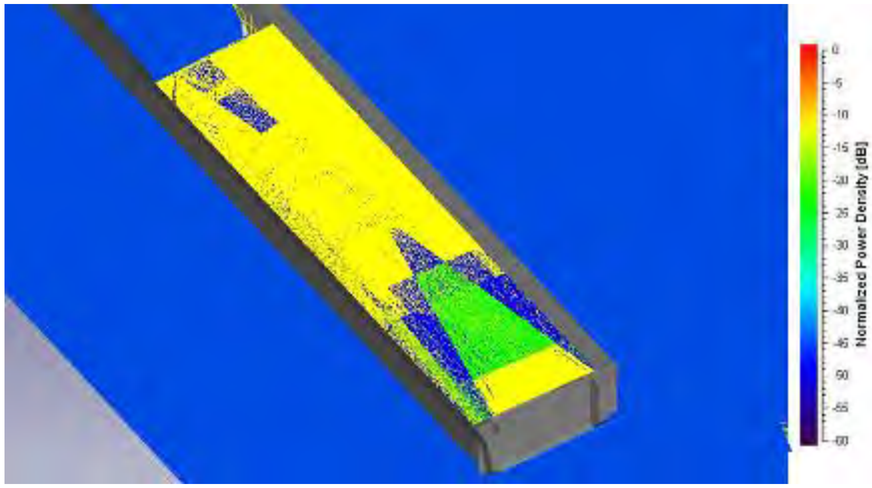

Figure 26. Savant ray trace output—2.4 GHz—antenna in the center; door closed.

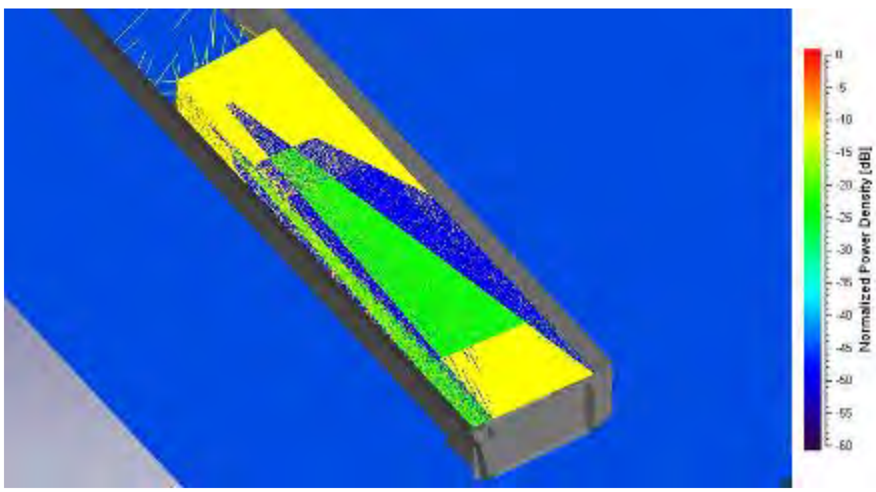

Figure 27. Savant ray trace output—5.8 GHz—antenna in a corner; door closed.

Changing the view, the signal distribution can be seen from another perspective. Figure 28 and Figure 29 show the side view for both frequencies. Both patterns are similar, changing the signal intensity abruptly in certain positions, as can be seen where the color changes as compared with the scale on the right-hand side of the figures.

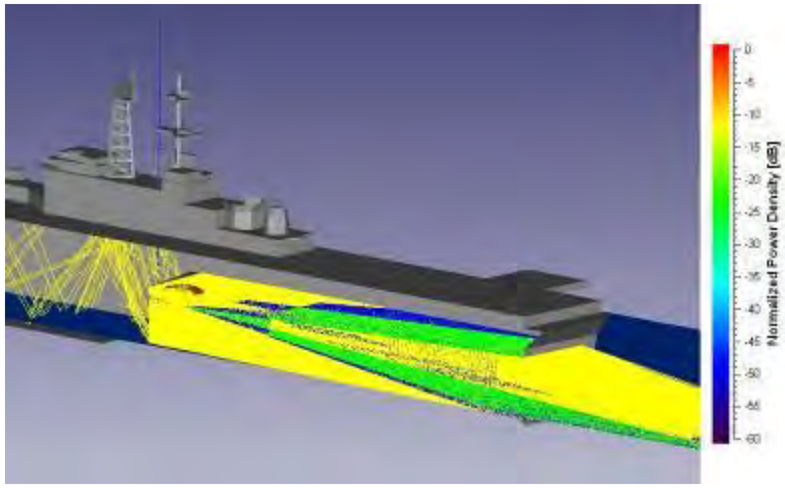

Figure 28. Savant ray trace output—2.4 GHz—antenna in the corner; door open.

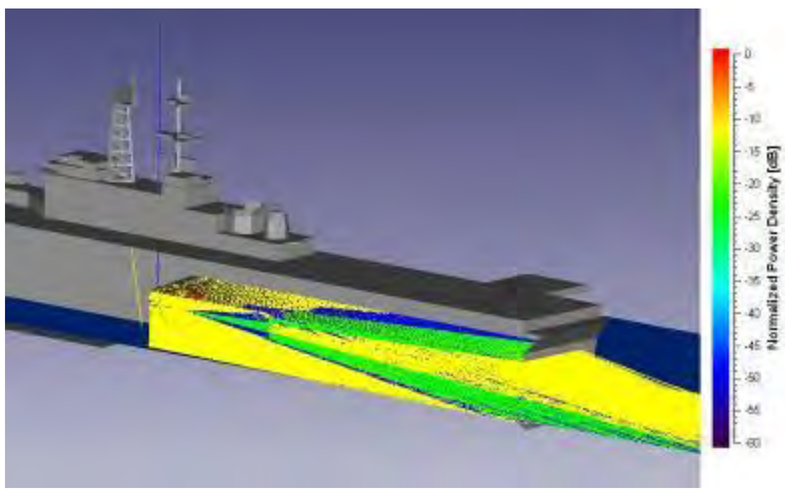

Figure 29. Savant ray trace output—5.8 GHz—antenna in the corner; door open.

Repeating the simulation when the door is closed, the results can be seen in Figure 30 and Figure 31.

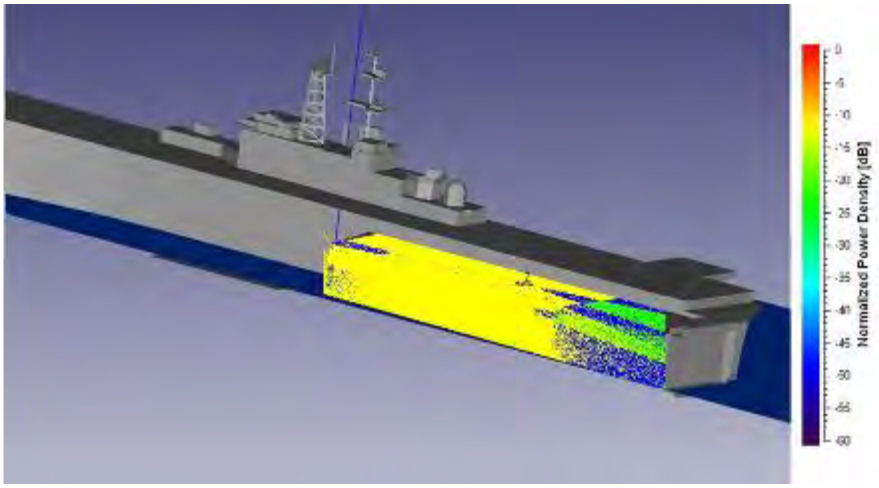

Figure 30. Savant ray trace output—2.4 GHz—antenna in the corner; door closed.

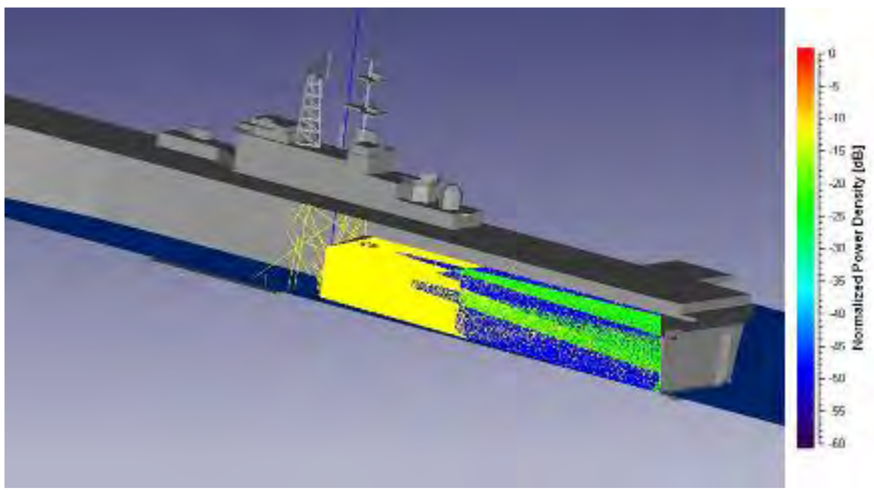

Figure 31. Savant ray trace output—5.8 GHz—antenna in the corner; door closed.

Considering different planes parallel to the sea, it can be observed that the signal changes its intensity for different heights. Figure 32 shows the power intensity for a plane at a height of 3 meters. Comparing this figure with Figure 33 and Figure 34 at different heights, the intensity changes in all directions, sometimes falling to low power intensity (blue and black). This pattern also changes every time the internal geometry is modified; that is, every time a person or an object change position within the room, the power distribution changes.

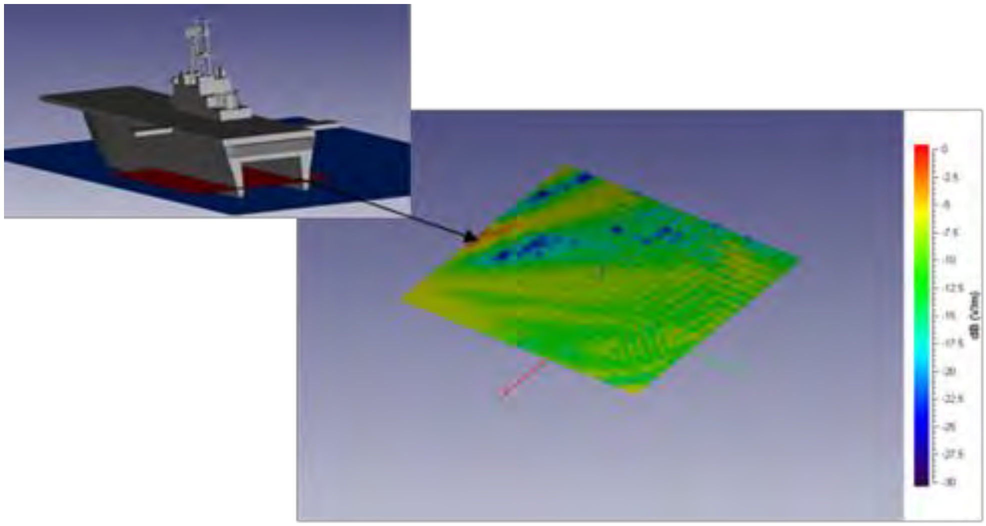

Figure 32. Signal intensity on a plane for a height of 3 meters—2.4 GHz.

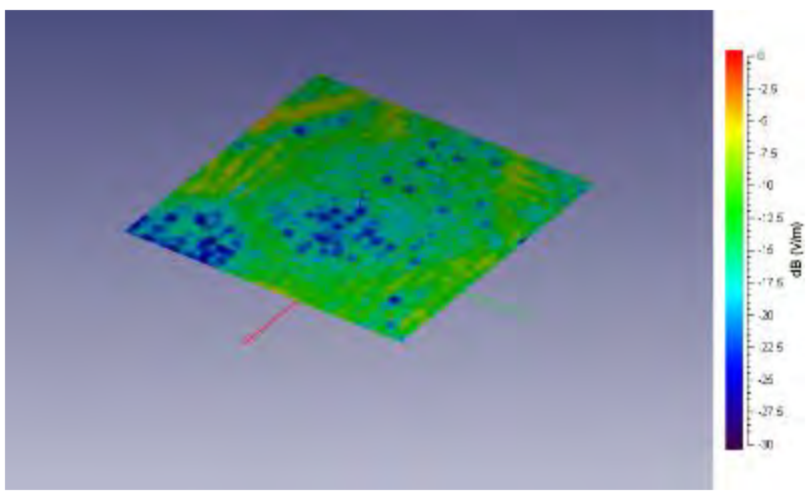

Figure 33. Signal intensity on a plane for a height of 6 meters—2.4 GHz.

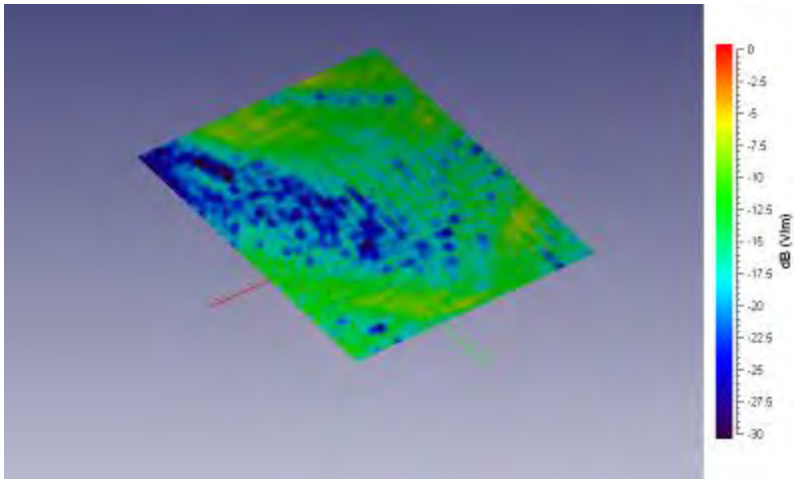

Figure 34. Signal intensity on a plane for a height of 9 meters—2.4 GHz.

Figure 35 shows the signal intensity for x = 10 meters and height = 9 meters. It is clear that the channel performance for a mobile device will be very low, given that the signal changes with its position and any other modifications in the surrounding environment.

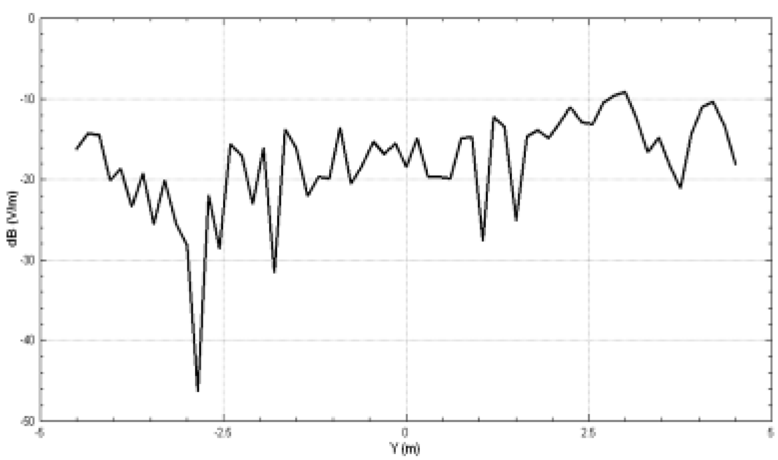

Figure 35. Line plot at x = 10 meters; height = 9 meters.

These simulation results include the most significant observations. Many others were obtained for both frequency bands and different conditions with similar observations and conclusions. They were not included in this thesis given that they do not add more information or details.

C. SUMMARY

The chaotic characteristics of the propagation in a simplified model could be observed, and how the signal intensity changes in a reflective room, resulting in the need to use other techniques to mitigate this problem, such as OFDM and MIMO. The power distribution within the room and how it changes abruptly in some areas could be observed, for different positions of the transmitting antenna. These positions were used in Chapter IV to take performance measurements of a WLAN inside a reflective room, using the features included in IEEE802.11ac to verify how effective they are in this environment.

IV. FIELD MEASUREMENTS AND RESULTS

This chapter presents the implementation of an 802.11ac WLAN in a highly reflective environment, such as a 40-foot metallic shipping container, in order to determine the performance for different positions and both frequencies. Considering the observations obtained in Chapter III, the metallic container serves as a sufficient analogue to measure how the new standard using OFDM and MIMO mitigates fading multipath. In each case, the data throughput were recorded and then analyzed to assess the performance of the 802.11ac WLAN in this scenario.

A. CONDITIONS

The measurements were taken inside a 40-foot metallic shipping container, modifying the position of the access point, and connecting it wirelessly to two different computers and a mobile device using both frequencies 2.4 and 5.8 GHz. The access point was mounted on a tripod at an approximate height of two meters and placed at different positions, as shown in Figure 36.

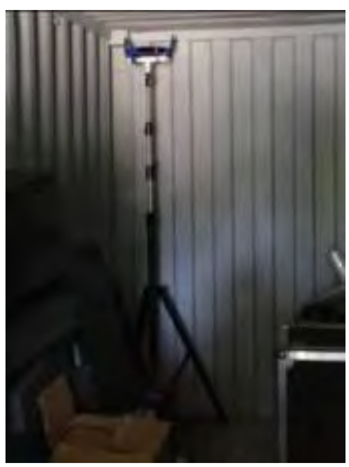

Figure 36. Access point on the tripod.

The positions were selected according to the observations in the simulations in Chapter III.B (Figure 23, Figure 24, and Figure 25**Error! Reference source not found.**). The computers were placed in the corner where the received power is the lowest, and the

access point was placed in four different positions, numbered from one to four, as seen in Figure 37.

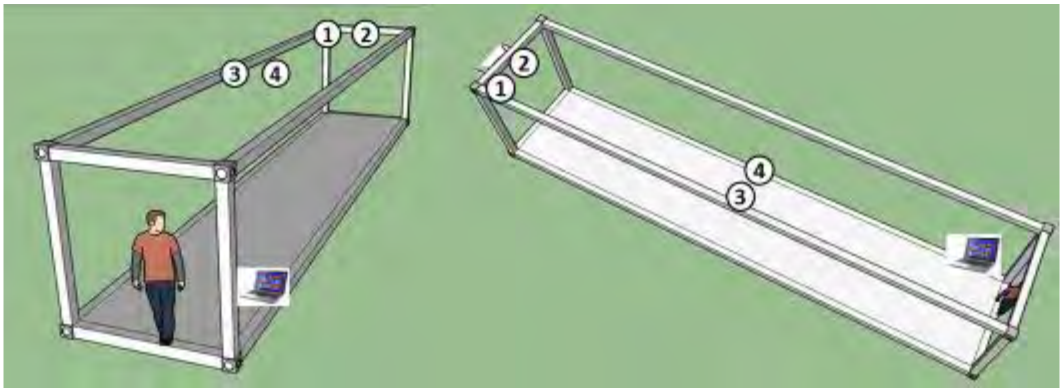

Figure 37. Positions of the computer and the access point within the container.

In a previous survey, using appropriate software, in this case in SSIDer 2.1 by Metageek, it was determined that there were no ambient signals in either 2.4 and 5.8 GHz bands, due to the isolation provided by the metallic walls. After turning on the access point, the spectrum was only occupied by the desired signals, as shown in Figure 38 and Figure 39.

Figure 38. Spectrum survey using inSSIDer 2.1–2.4 GHz.

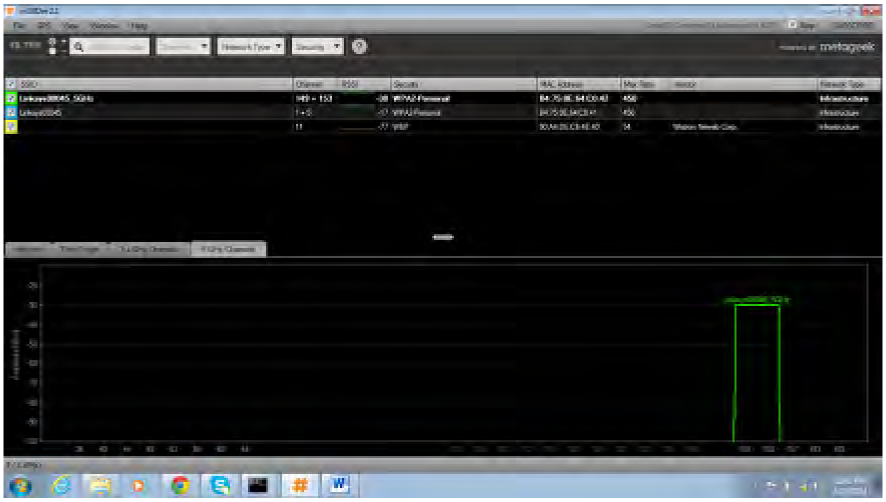

Figure 39. Spectrum survey using inSSIDer 2.1–5.8 GHz.

Figure 40 shows the topology used to take measurements. The web-browser interface of the Linksys wireless access point was used for the configuration by entering settings of the 802.11ac WLAN. It also provided necessary information about the radio interfaces and the principal parameters of interest, such as received signal strength.

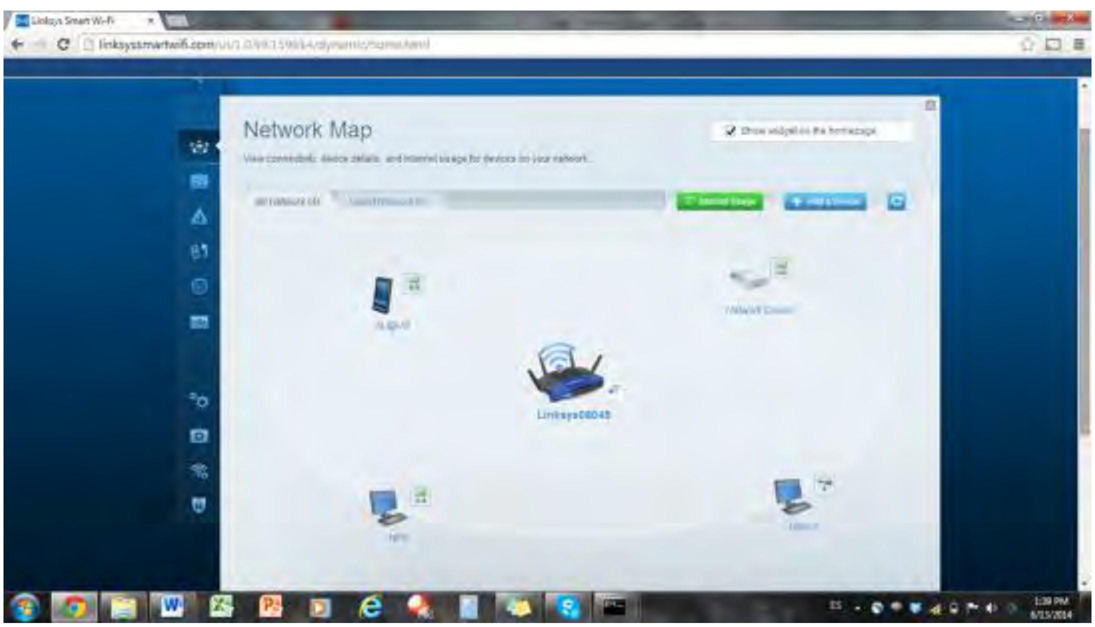

Figure 40. Topology used to take measurements.

As shown in Figure 41, two computers running Windows 7 were used within the metallic container to establish the wireless link to the access point and measure the performance. One Apple iPhone 5 was configured to perform some tests, as this cellular phone has an IEEE802.11n chip.

Figure 41. Computer working into the metallic container.

B. SELECTED EQUIPMENT

The equipment that was chosen for the implementation of the 802.11ac indoor WLAN, along with the architecture of the designed WLAN, is presented in this section. Several factors were taken into account for selecting the appropriate equipment.

There was interest in a temporary network infrastructure that would be rugged, flexible, and portable, as well as easy to install at different positions. Hence, in order to accomplish the task, wireless equipment from an industry-leading manufacturer, Linksys, formerly part of Cisco Systems, was selected and used. The *Linksys Dual-Band AC Router WRT1900AC* was the choice. This specific router can operate as an access point, a wireless bridge, or a workgroup bridge. For this research, the device was used exclusively as an access point. Two *Linksys Wireless AC 1200 Dual-Band USB Adapters (WUSB6300)* were used connected to the computers, to provide the same standard on both sides of the link.

1. Linksys Dual-Band AC Router WRT1900AC

The Linksys WRT1900AC Dual Band Wi-Fi Router (Figure 42) has a dual-core 1.2 GHz processor, four removable antennas, and eSata and USB 2.0/3.0 connectivity ports. It also includes management tools and a Network Map feature. This last feature was used to generate Figure 40. The four removable, customized, and adjustable antennas provide antenna diversity enabling the router to use the three best signals out of the four antennas to transmit and receive data [12].

It is capable of speeds of up to 1.3 Gbps on the 5 GHz band, and up to 600 Mbps on the 2.4 GHz band; both speeds are the maximum performance for a wireless derived from the IEEE Standard 802.11 specifications [12]. The main characteristics are included in Table 4.

Table 4. Specifications of the LinksysWRT1900AC, from [12].

Technology	Wireless-N & AC
Bands	2.4 & 5 GHz
Processor	1.2 GHz dual-core ARM-based
Antennas	4 x External antennas
Ports	4 x Gigabit LAN, 1 x Gigabit WAN, 1 x USB 3.0
Power Adapter	100-240V -50-60- Hz
VPN Support	PPTP IPSec pass-through
Memory	128MB Flash, 256MB DDR3 RAM
OS compatibility	Windows, Mac

Figure 42. LinksysWRT1900AC.

2. Linksys Wireless USB Adapter AC 1200 Dual Band

The Linksys Wireless USB Adapter AC 1200 Dual Band (Figure 43) is a compact wireless device used for connecting a computer to an existing wireless network or hotspot. It is compatible with most of the wireless 802.11ac routers, access points, and extenders [13]. The main characteristics of this device are included in Table 5.

Table 5. Specifications of the Linksys AC1200, from [13].

Technology	Wireless AC
Bands	2.4 GHz or 5 GHz
Antennas	2 Internal
OS Compatibility	Windows
System Requirements	PC running Windows XP SP3, Windows Vista SP1 or later, Windows 7, Windows 8 - Available USB 3.0 port

Figure 43. WUSB6300 USB WiFi Wireless AC Dual-Band Linksys AC1200.

C. MEASUREMENTS AND RESULTS

This section provides a description of the measurements taken from the implementation of the WLAN, the methods used to take these measurements, and an analysis of the results.

1. Packet Internet Groper

Packet Internet Groper (PING) is a utility that can verify if the network protocol is working, configured correctly, and communicating with other devices. It is often

employed simply to determine whether a host is responding. PING sends Internet Control Message Protocol (ICMP) echo request and echo reply messages that determine the validity of an IP address. First, a signal, called an echo request, is sent out to another network device as well as the connectivity between the source and destination entities. The other device then responds to the sender, in the form of an echo reply [14].

The utility also measures the time elapsed between when the echo request was sent and when the echo reply was received. This feature can be used as a simple tool to evaluate the stability of the data communication link between two devices connected to the network by observing if the delay changes [14]. It is an easy method to implement and gives a general indication of the link stability.

This test was performed several times from different locations within the container, observing the stability impact of moving the mobile devices (computer and cellular phone). Figure 44 shows the output when pinging the access point from a computer moving inside the container, working at 2.4GHz. It can be observed that the time delay remains stable at 1ms.

Using a cellular phone (an Apple iPhone 5), running a popular application to implement the PING utility called *Mocha Ping Lite*, the stability can also be observed. As mentioned before, this cellular phone corresponds to a previous standard, also resulting in good performance. Figure 45 shows the screen when performing the application in 2.4 GHz. The difference in delays between the two devices is due to different processing times for the device applications.

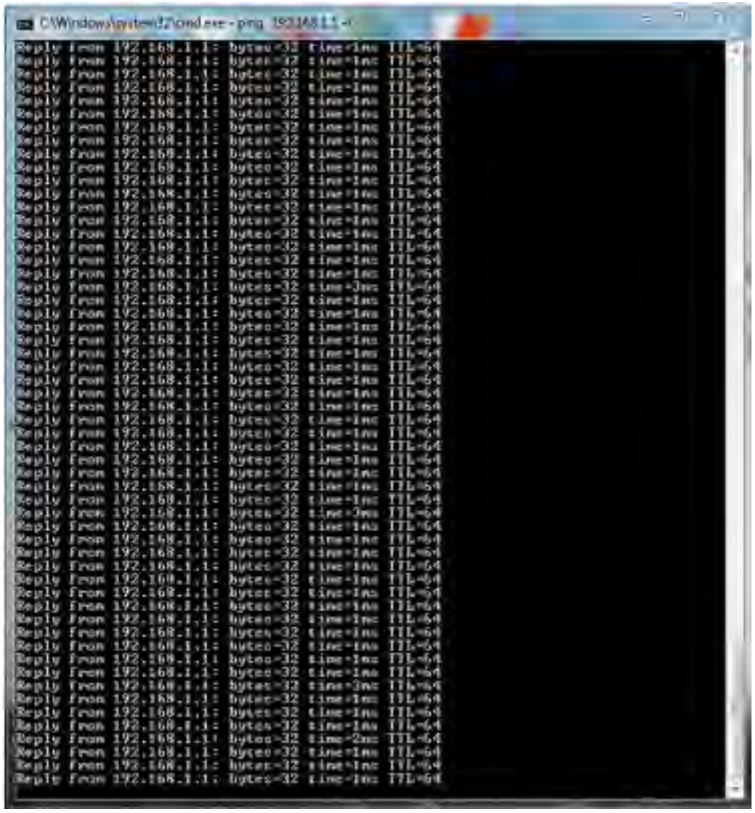

Figure 44. Pinging the access point from a PC at 2.4 GHz.

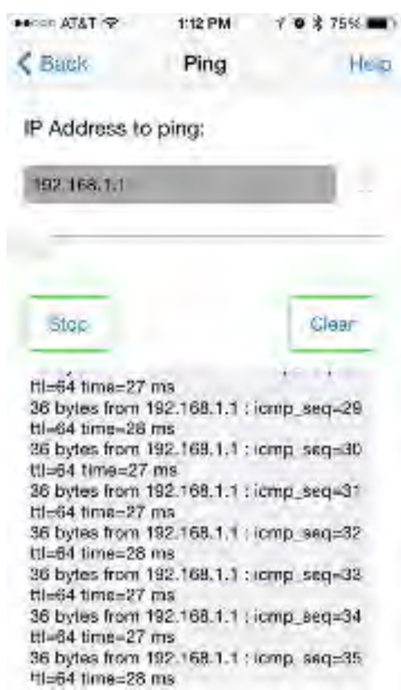

Figure 45. Pinging the access point from a cellular phone at 2.4 GHz.

Repeating the experiment at 5.8GHz from a PC and the same cellular phone, the output results were similar to the previous one, as shown in Figure 46 and Figure 47, with a delay of about 1 ms.

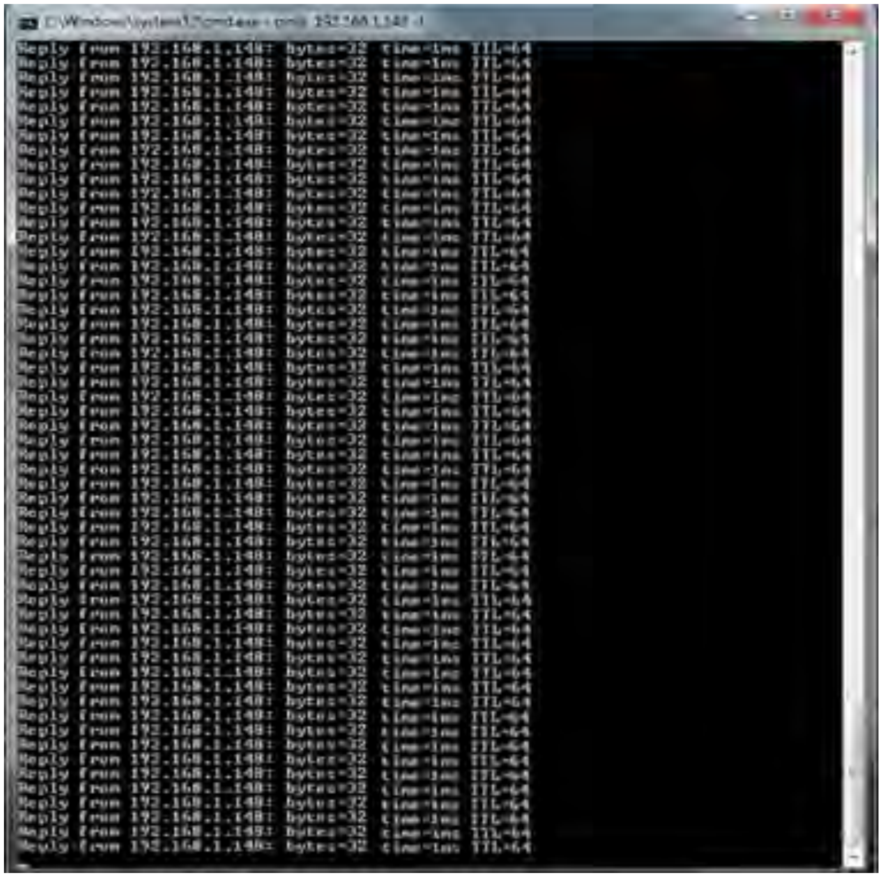

Figure 46. Pinging the access point from a PC at 5.8 GHz.

Figure 47. Pinging the access point from a cellular phone at 5.8 GHz.

It is observed that the data transmission results were stable for both frequencies. After reconfiguring the access point to use a previous standard (IEEE802.11g), the resulting output was unstable for the same conditions, as shown in Figure 48.

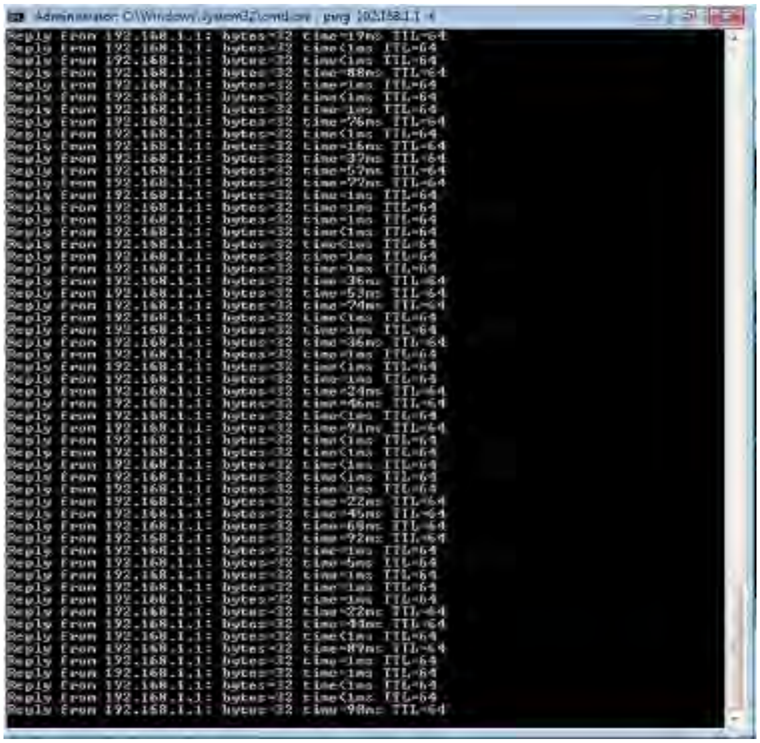

Figure 48. Pinging the access point using 802.11g from a PC.

This comparison means that the implementation of the new standard IEEE802.11ac improves the data link performance, as can be seen in Figure 49.

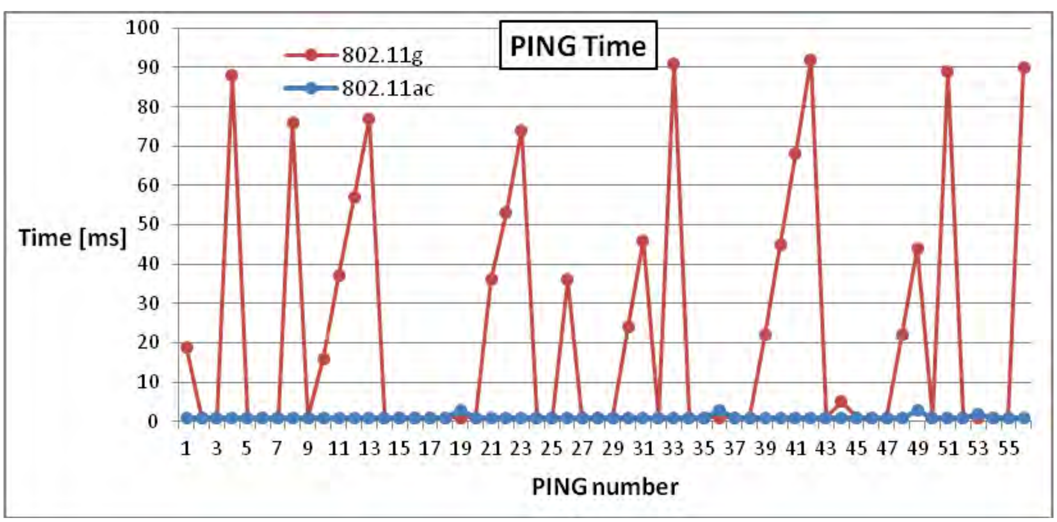

Figure 49. PING time for 802.11ac and 802.11g (2.4 GHz).

2. Effective Data Throughput

This measurement was conducted transferring two different sized files between two computers, one of approximately 25 Mbytes and another one of approximately 100 Mbytes. In this case, one computer was connected to the access point via an Ethernet cable to leave the wireless channel to be used for only one link between the other computer and the access point, resulting in a two-hop connection between the sending host and the receiving host.

a. Using a 25 Mbytes File

The measurements were carried out using two different frequencies and several positions for the access point inside the metallic container. The effective data rates are shown in Table 6, according to the positions described in Figure 37.

Table 6. Effective data rate results using a 25 Mbytes file.

Position	2.4GHz		5.8GHz	
	Time [sec]	**Data rate [Mbps]**	**Time [sec]**	**Data rate [Mbps]**
1	0.42	499.3	0.21	998.6
2	0.41	511.5	0.22	953.3
3	0.43	487.7	0.20	1048.6
4	0.40	524.3	0.21	998.6

b. Using a 100 Mbytes File

The same exact measurements were repeated with a file size of approximately 100 Mbytes. The results for the effective data rate are tabulated in Table 7.

Table 7. Effective data rate results using a 100 Mbytes file.

Position	2.4GHz		5.8GHz	
	Time [sec]	Data rate [Mbps]	Time [sec]	Data rate [Mbps]
1	1.62	517.8	0.82	1023.0
2	1.63	514.6	0.85	953.3
3	1.70	493.4	0.79	1061.8
4	1.59	527.6	0.81	1035.6

3. Summary of the Results

Under reflective conditions, the resulting measurements were stable for all conditions and better than previous versions of the 802.11 standard, as could be seen from the simple PING test. As expected, the effective data rate resulted in lower than the maximum performance established by the manufacturer of the access point (see IV.B.1. Linksys Dual-Band AC Router WRT1900AC) given that this last data rate specification includes overhead and does not include some processing delays. However, these considerations are part of hardware implementation and not an evaluation of how the standard solves the instability due to fading multipath. Independent of implementation issues, it is more important to observe that the link was stable, even when the position was changed, demonstrating that the standard is capable of working in this kind of environment.

D. SUMMARY

This chapter presented the results obtained during the collection of field data under reflective conditions from two different experiments. Using the PING utility, a simple comparison was performed to determine that the new standard improved the performance. The link was tested at different distances between the network devices and the access point. In all cases, the performance was the same. The IEEE802.11ac standard resulted in a very stable link, performing at an effective data rate.

V. CONCLUSIONS AND FUTURE WORK

This chapter summarizes the results of this thesis and makes suggestions for additional research about wireless technologies, and how to use them within reflective rooms.

A. CONCLUSIONS

The primary objective of this thesis was to investigate the WLAN performance in reflective compartments, and explore the ability of COTS WiFi to mitigate the negative effects of the propagation characteristics inside such rooms. Radio wave propagation presents difficulties for WLANs implemented in reflective rooms due to multipath fading. Consequently, a WLAN, such as an IEEE 802.11 based WLAN, faces problems working in these areas. This thesis explored the performance of an 802.11 network under such conditions. Particularly, the emerging IEEE 802.11ac standard was selected for this research based on its ubiquitous compatibility with commercially available software and hardware elements and its advanced antenna and signaling properties.

Considering these particular characteristics, and using simplified conditions for a well deck in an amphibious ship, Savant software was used to simulate the propagation in order to determine how much the signal intensity varies for the frequencies involved (2.4 and 5.8 GHz). These measures included placing the simulated transmitting antenna in the interior part of the simulated ship, developed with the SketchUp software and exported to Savant to run a series of simulations to assess the signal distribution inside of the compartment model developed earlier.

The simulation results depicted the signal distribution over a plane of observation points representing the locations of possible wireless devices. It was observed that the signal was very unstable for different positions and moments, resulting in difficult conditions for wireless mobile devices.

Using the positions determined by simulation as the worst propagation cases, a WLAN based on the standard IEEE802.11ac was implemented and tested in this particular reflective operational environment from. The wireless devices that were

selected for the implementation of the network included a low-cost, commercially available portable wireless access point and USB wireless adapters from Linksys. This specification includes new features, such as OFDM and MIMO, which help to mitigate the effects of the multipath fading. This experiment confirms that the new features of IEEE 802.11ac effectively mitigate such fading and result in a good possibility of having wireless access to the network during tactical and logistics operations using mobile devices.

The conclusion is that the indoor 802.11ac WLAN, implemented in a highly reflective operational environment, can be successfully used for military operations in this environment. This implementation would allow access to Command and Control or logistics applications during operations, adding flexibility and mobility to the military needs. Further, providing this access to personnel within amphibious vehicles in the well deck could provide communications between well decks of several ships by leveraging the host vessels' network infrastructure and inter-ship links, thereby facilitating pre-debarkation collaboration between landing forces.

B. FUTURE WORK

Onboard Measurements: One important practical test that might be conducted in the future is the implementation and measurement of the WLAN within an actual well deck or hanger bay, which this thesis was unable to do due to access limitations. This test should be oriented to evaluate not only WLAN performance, but also Electromagnetic Interference (EMI) from other systems. This problem causes issues when implementing a WLAN.

EMI is the disruption of the operation of an electronic device when it is in the vicinity of an electromagnetic field in the RF spectrum that is caused by another electronic device. The internal circuits of diverse electronic devices generate EM fields in the RF range. These emissions can decrease the performance of sensitive wireless receivers nearby. High-powered wireless transmitters of radar and communication systems can produce EM fields strong enough to disrupt the operation of other electronic equipment nearby.

Conversely, whether the WLAN radiation itself affects any other sensitive electronic device aboard the ship, such as sensors or communication systems, should also be determined.

Real-Time Applications: This thesis presented the results of the deployment of an 802.11ac WLAN transferring non-real time data. It would be interesting in the future to test the performance of real-time applications, such as VoIP or streaming media, under the same reflective conditions. This new research might include different real-time protocols and could lead to the extension of the phone network to new areas wirelessly, increasing Command and Control capabilities.

Mesh Networks: The Mesh Network concept includes certain capabilities that might improve the wireless performance in reflective areas. It can create a dynamic topology of several nodes, enabling data delivery on single-hop and multi-hop paths.

The drawback is the use of several frequencies to connect to the different nodes, which is a disadvantage for these environments. However, it could be considered as frequency diversity. This implementation may considerably increase the wireless coverage area, and do it more reliably. Additionally, other COTS wireless technologies, other than 802.11 WiFi, might be considered and their performance compared to the baseline established by this thesis.

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